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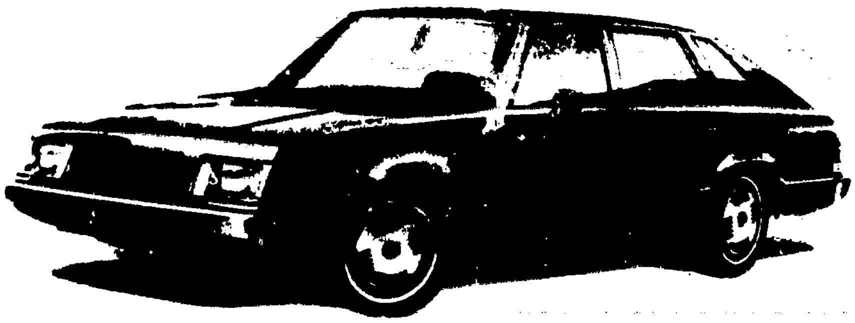
NEAR-TERM HYBRID VEHICLE PROGRAM

FINAL REPORT — PHASE I

Appendix B — Design Trade-Off Studies Report

Vol II — Supplement to Design Trade-Off Studies



Contract No. 955190

Submitted to

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103

Submitted by

General Electric Company
Corporate Research and Development
Schenectady, New York 12301

October 8, 1979

GENERAL ELECTRIC

SRD-79-134/4

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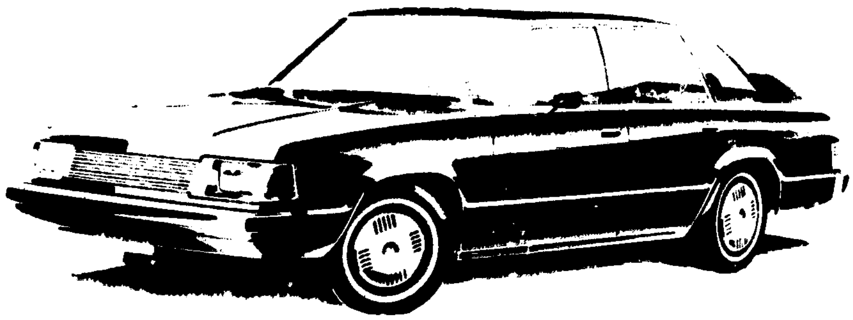

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GENERAL ELECTRIC

FOREWORD

The Electric and Hybrid Vehicle (EHV) Program was established in DOE in response to the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. Responsibility for the EHV Program resides in the Office of Electric and Hybrid Vehicle Systems of DOE. The Near-Term Hybrid Vehicle (NTHV) Program is an element of the EHV Program. DOE has assigned procurement and management responsibility for the Near-Term Hybrid Vehicle Program to the California Institute of Technology, Jet Propulsion Laboratory (JPL).

The overall objective of the DOE EHV Program is to promote the development of electric and hybrid vehicle technologies and to demonstrate the validity of these systems as transportation options which are less dependent on petroleum resources.

As part of the NTHV Program, General Electric and its subcontractors have completed studies leading to the Preliminary Design of a hybrid passenger vehicle which is projected to have the maximum potential for reducing petroleum consumption in the near term (commencing in 1985). This work has been done under JPL Contract 955190, Modification 3, Phase I of the Near-Term Hybrid Vehicle Program.

This volume is part of Deliverable Item 7, Final Report, of the Phase I studies. In accordance with Data Requirement Description 7 of the Contract, the following documents are submitted as appendices:

APPENDIX A is the Mission Analysis and Performance Specification Studies Report that constitutes Deliverable Item 7 and reports on the work of Task 1.

APPENDIX B is a three-volume set that constitutes Deliverable Item 2 and reports on the work of Task 2. The three volumes are:

- Volume I -- Design Trade-Off Studies Report
- Volume II -- Supplement to Design Trade-Off Studies Report, Volume I
- Volume III -- Computer Program Listings

APPENDIX C is the Preliminary Design Data Package that constitutes Deliverable Item 3 and reports on the work of Task 3.

APPENDIX D is the Sensitivity Analysis Report that constitutes Deliverable Item 8 and reports on Task 4.

The three classifications - Appendix, Deliverable Item, and Task number - may be used interchangeably in these documents. The interrelationship is tabulated below:

Appendix	Deliverable Item	Task	Title
A	1	1	Mission Analysis and Performance Specification Studies Report
B	2	2	Vol. I - Design Trade-Off Studies Report
			Vol. II - Supplement to Design Trade-Off Studies Report
			Vol. III - Computer Program Listings
C	3	3	Preliminary Design Data Package
D	8	4	Sensitivity Analysis Report

This is Volume II, Supplement to Design Trade-Off Studies Report Volume I, of Appendix B. This volume reports on work done on Task 2 and is part of Deliverable Item 7, Final Report, which is the summary report of a series which documents the results of Phase I of the Near-Term Hybrid Vehicle Program. Phase I was a study leading to the preliminary design of a five-passenger vehicle utilizing two energy sources (electricity and gasoline/diesel fuel) to minimize petroleum usage on a fleet basis.

This volume presents reports submitted by subcontractors on heat engines, battery power sources, and vehicle technology. These subcontractor reports have been reproduced as submitted to General Electric and are presented in this volume to make available source material that was used in the Design Trade-Off Studies.

The subcontractor reports are submitted in separate sections in which the General Electric imposed Work Statement is presented first, followed by the subcontractor report submitted in response to the Work Statement. The order of presentation is

Section 1 - Heat Engine Trade-Off Study performed by General Electric Company, Space Division

Section 2 - Assessment of Battery Power Sources performed by ESB Technology Company

Section 3 - Vehicle Technology performed by Triad Services, Incorporated

Material from a number of internal General Electric studies which were used during the Design Trade-Off Studies was summarized and is presented in Section 4 - Motors and Controls for Hybrid Vehicles. Included in Section 4 are attachments which describe pertinent studies and developments. These are:

Attachment A - Proposed Development Program on Advanced Electric Vehicle, October 1975

Attachment B - Centennial Electric Car

Attachment C - Electric Vehicle AC Drive Study

Attachment D - Propulsion System Design Trade-off Studies

Attachment E - Producibility Analysis

Attachment F - Required Motor and Controller Data

The attachments are submitted without any editorial rewrite or attempt to present a continuously narrative text but only as a means to record background information.

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HEAT ENGINE TRADE-OFF STUDY

GENERAL ELECTRIC

WORK STATEMENT

to

General Electric Company
Space Division
Space Systems Operatior
Philadelphia, PA 19101

INTRODUCTION

Contract No. 955190 between California Institute of Technology Jet Propulsion Laboratory and General Electric Company covers a program entitled "Phase I of the Near-Term Hybrid Passenger Vehicle Development Program" under which studies shall be conducted leading to a preliminary design of a hybrid passenger vehicle that is projected to have the maximum potential for reducing petroleum consumption in the near term (commencing in 1985). Effort under Contract 955190 is being conducted pursuant to an Interagency Agreement between the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) and in furtherance of work under Prime Contract NAS7-100 between NASA and the California Institute of Technology. This work statement covers heat engine technology under General Electric Purchase Order A02000-220406.

SCOPE OF WORK

In support of General Electric Corporate Research and Development's work under Contract 955190, the Subcontractor shall furnish the necessary personnel, materials, services, facilities, and otherwise do all things necessary for or incident to the performance of the following tasks:

1. Provide a description of the system and components of state-of-the-art electronic fuel gasoline engines:
   - Engines currently being marketed
   - Engines in advanced stage of development of testing
   - System components and control
   - Sensors
   - Microprocessors and control logic
2. Consider the use of fuel-injected engines in the on/off operating mode:
   - Fuel cutoff techniques
   - Engine startup at relatively high vehicle velocity ($\approx$30 mph)

- Emissions (steady-state NO_x emissions, sizing catalyst, warmup, fuel cutoff during deceleration)
- Thermal effects and cooling
- Accessory drives
- Engine durability

3. Selection and characterization of fuel-injected engines in the 60 - 80 hp range (probably four-cylinder) for use in the hybrid vehicle.

NOTE WITH RESPECT TO SUBCONTRACTOR'S DATA

It is understood that all data furnished hereunder may be furnished to the California Institute of Technology Jet Propulsion Laboratory and DOE and NASA with no restrictions.

HEAT ENGINE TRADEOFF STUDY
NEAR-TERM HYBRID VEHICLE PROGRAM - PHASE I

PREPARED BY:

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Purchase Order No. A02000-220406

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HEAT ENGINE TRADEOFF STUDY

NEAR-TERM HYBRID VEHICLE PROGRAM - PHASE I

INTRODUCTION

A heat engine/electric hybrid vehicle will employ heat engine power for high speed (e.g. above 30 MPH) cruising, and electric power for low speed cruising, acceleration, passing and hill-climbing. When the engine is turned on it will operate at or near the wide-open throttle (WOT) conditions to maximize its efficiency.

For a five-passenger highway vehicle cruising at a steady speed of 90 Km/hr (50 MPH), the power requirement is in the order of 30 HP. Since the engine efficiency peaks at 40 to 50% of the maximum engine speed, the engine maximum rated power should be sized between 60 to 80 HP for a hybrid vehicle.

1.0 PRELIMINARY SCREENING OF ENGINE TYPES

1.1 Selection Criteria

Since the electric system (batteries, generator and motor) serves as a second prime mover, the cost, weight and volume constraints of a hybrid heat engine are more stringent than in conventional automobiles. The desired hybrid engine should be light-weight, durable and cost effective.

A hybrid engine should meet the 1981 Federal Statutory Emission Standard as a conventional automobile. For modes of operation involving on-off, the emission control techniques developed for conventional automobiles can be adopted.

Another consideration of the hybrid engine is its speed compatibility with the electric generator, especially for the system configurations where a direct coupling between the two components is required. For the on-off modes of operation, the fuel economy sensitivity to the speed or load variation also becomes an important consideration.

In order to develop an engine by 1980 and for it to be ready for mass production by 1985, the present product maturity of the candidate hybrid engines is an important parameter in making the final selection of a heat engine for a near-term hybrid vehicle.

1.2 Candidate Engines

To make a rational selection of the most suitable hybrid engine, a set of screening criteria, which are based upon the requirement discussed above, are developed. All feasible heat engines are identified and a gross evaluation of the engine characteristics against the screening criteria are performed for the selection of preliminary candidates A more in-depth tradeoff study of these preliminary engine candidates are followed and reported in the following sections.

Table 1 shows such a matrix. The goal of the rated power range is set to be from 60 to 80 HP. The fuel consumption, weight and cost of various engine types, as classified by different thermodynamic cycles, are presented as the average value of each type relative to a typical conventional spark-ignition gasoline engine of equivalent power rating.

1.3 Engine Type Selection

From a fuel consumption point of view, turbo-charged diesel, Stirling and regenerative type gas-turbine engines offer better efficiencies than gasoline engines. However, both the Stirling engine and the gas-turbine in the 60 to 80 HP range are still in early developmental stages. Their availability for a 1980 demonstration will require substantial developmental efforts. Even though a 50 HP VW diesel engine is currently on market, it is not selected for the present study due to the uncertainty in the future Federal regulation on the exhaust particulate emission.

Advance developments in the recent years on the Otto-cycle engines, particularly on fuel delivery and the emission controls, have improved their fuel consumption significantly while successfully meet the Federal emission requirements. To select an efficient and reliable engine for the near-term hybrid vehicle without substantial development of the engine system, an advanced Otto-cycle engine appears to be most attractive.

Engine Type	Relative Fuel Consumption	Emissions	Relative Weight	Noise	Relative Cost	Reliability & Maintenance	Other Characteristics	Critical Elements	Developed By 1980	Production By 1985
Otto Cycle										
Reciprocating:										
Conventional	1.0	High NOx&Co	1.0	Mod.	1.0	Good	Fuel economy sensitive to speed/load.	Catalyst	Yes	Yes
EFI	.82	Low	1.0	Mod.	1.3	Good		Catalyst	Yes	Yes
Stratified Charged	.90	Moderate	1.0	Mod.	1.2	Good		None	Yes	Yes
Lean Mixture	.94	Low	1.0	Mod.	1.4	Good		None	Possible	Possible
Turbo-Charged	.86	High NOx	0.8	Slightly Higher	1.5	Good		Turbo matching	Yes	Yes
Rotary-Wankel	1.2	High HC	0.6	Lower	1.2	Good	Direct coupling to elec. gen. or driveshaft	Seals	Yes	Yes
Diesel Cycle										
Naturally-Aspirated	.8	High NOx Smoke & Odor	1.3	High	1.6	Excellent	Good Fuel Economy over Wide Speed/Load Ranges.	none	Yes	Yes
Turbo-Charged	.72	High NOx Smoke & Odor	1.1	High	1.8	Excellent		none	Yes	Yes
Stirling Cycle										
Rhombic Drive	.78	Extremely Low	1.3	Low	2.0	Good	Fuel Economy Sensitive to Speed	Seals High Temp. material	Yes	Yes (with major effort)
Brayton Cycle										
Non-Regenerative	1.5	High NOx	0.7	Low	2.0	Excellent	Fuel Economy Sensitive to Speed/Load	High Temp material	Yes	Yes
Regenerative	.9	High NOx	0.7	Low	2.2	Good	Need Speed Reduction Gear	High Temp. regenerator	Doubtful	Doubtful
Rankine Cycle										
Steam	1.2	Low	1.3	Low	1.8	Good	Fuel Economy sensitive to Speed/Load	none	Yes	Yes (with major effort)
Organic Fluid	1.9	Low	0.6	Low	1.8	Fair	Need Speed Reduction Gear	organic fluids	Yes	Yes (with major effort)

*REFERENCES 1-14

1.4 Selection of An Otto-Cycle Engine

The air/fuel ratio for a spark-ignition gasoline engine should be carefully controlled in order to achieve the optimum engine efficiency which is obtained at an equivalence ratio, λ, of approximately 1.1 where:

$$\lambda = \frac{\text{actual volume of air drawn into engine}}{\text{theoretical requirement of air for stoichiometric combustion}}$$

The specific fuel consumption deteriorates rapidly as λ moves away from 1.1.

On the other hand, to meet the stringent exhaust emission regulations while maintaining a good engine performance, use of a three-way catalytic converter appears to hold the most promise in early 1980's (Reference 12). To achieve high conversion efficiencies for all exhaust emissions -- unburnt hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NO_x), the engine should be operated at an equivalence ratio around 1.0 and maintained it within a narrow range of ± 0.01.

The electronic fuel injection system with a feedback control of an oxygen sensor at the exhaust makes it possible to achieve the accurate control of the fuel delivery rate within the above narrow range. It has demonstrated capabilities and advantages which include:

- Reduction of exhaust emission below the levels required by the 1981 Federal Statutory Emission Standards.
- Good vehicle performance and drivability.
- Reliable.

The technology has been well-demonstrated in many passenger cars currently in the market. Maturity of the technology and hardware as well as the demonstrated good performance and low emission make the EFI engine coupled with a three-way catalyst a logical choice for the hybrid vehicle in the early 1980's.

So far a stratified-charged spark-ignition (SI) engine, such as the Honda engine (Reference 14), has not demonstrated its ability to meet 1981 Federal emission standards without additional emission control equipment, such as a catalyst. Its fuel consumption is also not as good as a well-tuned EFI engine. The Ford Proco engine is still in the development stage and little information is available.

A turbo-charged V-6 SI engine has been marketed by Buick in 1978. The power output has been increased by 50%. However, so far a potentially better fuel economy has not been realized to a great extent (Reference 13). At WOT the fuel consumption is, in fact, poorer due to a fuel-rich requirement to help control detonation. Further technology development will be required until the turbo-charged SI engine becomes an attractive candidate for hybrid application.

2.0 DESCRIPTION OF SYSTEM AND COMPONENTS

2.1 Engine Currently Being Marketed

Development of Electronic Fuel Injection (EFI) systems started in the 1950's. Approximately 300 systems were first introduced by Chrysler Corporation during model year 1958. Concerns on exhaust emission control in the late 1960's led to a more successful development in EFI. Robert Bosch of West Germany succeeded in marketing the first high volume production EFI system to Volkswagon in 1967. The EFI system developed by Bendix Corporation was introduced by Cadillac in its 1975 model. At the present time, EFI systems have been quite popular among many passenger car models. Table 2 lists some of the EFI engines and their emissions and performance data which are currently marketed. It is interesting to note that so far the only engines meeting 1981 emission standards, especially NO_x, are those using three-way catalysts.

EFI systems for most of the foreign cars are developed by Robert Bosch, while for domestic cars, Bendix Corporation is the major supplier.

The electronic engine control system developed by Ford Motor Company applies a similar principle as the EFI systems. Instead of using injectors for fuel delivery, Ford selected to modify the conventional carburator with a feedback control loop. In addition, data available (Reference 21) is not as extensive as that on the EFI systems. Therefore, the Ford system is not included in Table 1 as one of the Electronic Fuel Injection systems.

TABLE 2. EFI - ENGINES CURRENTLY BEING MARKETED

CAR MODEL	(YEAR)	TYPE	EMISSION CONTROL	EMISSION LEVELS (gm/mile) HC	CO	NOx	FUEL ECONOMY (MPG) CITY	HIGHWAY
VW	(76)	L4, 97 CID	EGR/OXI. CAT.	0.3	4.8	0.8	26	38
SAAB	(78)	L4, 121 CID	3-WAY CAT.	0.19	3.9	0.28	22	30
	(77)		EGR/AIR INJ.	0.89	6.0	1.7	22	31
VOLVO	(77)	L4, 130 CID	3-WAY CAT.	0.2	2.7	0.18	18	28
	(76)		EGR/AIR INJ.	0.8	9.1	1.9	18	25
	(78)	V6, 163 CID	3-WAY CAT.	0.35	3.6	0.85	16	26
	(77)		EGR/OXI. CAT.	0.2	1.1	1.25	14	26
	(76)		EGR/AIR INJ.	1.3	13.0	2.6	15	27
BMW	(76)	L4, 122 CID	EGR/AIR INJ.	0.4	5.0	1.4	20	30
AUDI	(77)	L4, 97 CID	EGR/OXI. CAT.	0.2	2.0	1.2	24	36
	(77)	L4, 114 CID	EGR/OXI. CAT.	0.3	2.3	1.4	18	26
AMC		L4, 122 CID						
CADILLAC		V8, 500 CID						
1981 FEDERAL EMISSIONS STANDARDS:				0.4	7.0	1.0		

2.2 Advanced Engines under Development

There is expected to be no major technology break-through in the passenger car engine between now and the early 1980's. Existing basic engine types will be pretty much maintained. Major efforts in the near-term engine development are in the fine-tuning of the existing engine types, especially in a better control of fuel/air mixture through the improvement of either a carburator or fuel injection systems. It is believed that most of the fine-tuning techniques developed in the next few years can be adopted in the heat engine selected for the near-term hybrid vehicle.

2.3 System Components and Control

The basic system, components and control of an electronic fuel injection system for gasoline engines has been described in detail in published literature (References 15-22). Despite some differences in design details among various systems, their basic principle of operation is similar. In these systems, detecting elements sense the engine operating conditions and pass their information in the form of electric signals to an electronic control unit. Processing these signals, the control unit then determines the amount of fuel required by the engine and controls the proper fuel delivery to insure proper air/fuel ratio.

A typical EFI system is schematically depicted in Figure 1. Figure 2 shows a simplified block diagram of its feed-back control. The system generally consists of four subsystems: the fuel delivery, the air-induction, the primary sensors, and the electronic control unit.

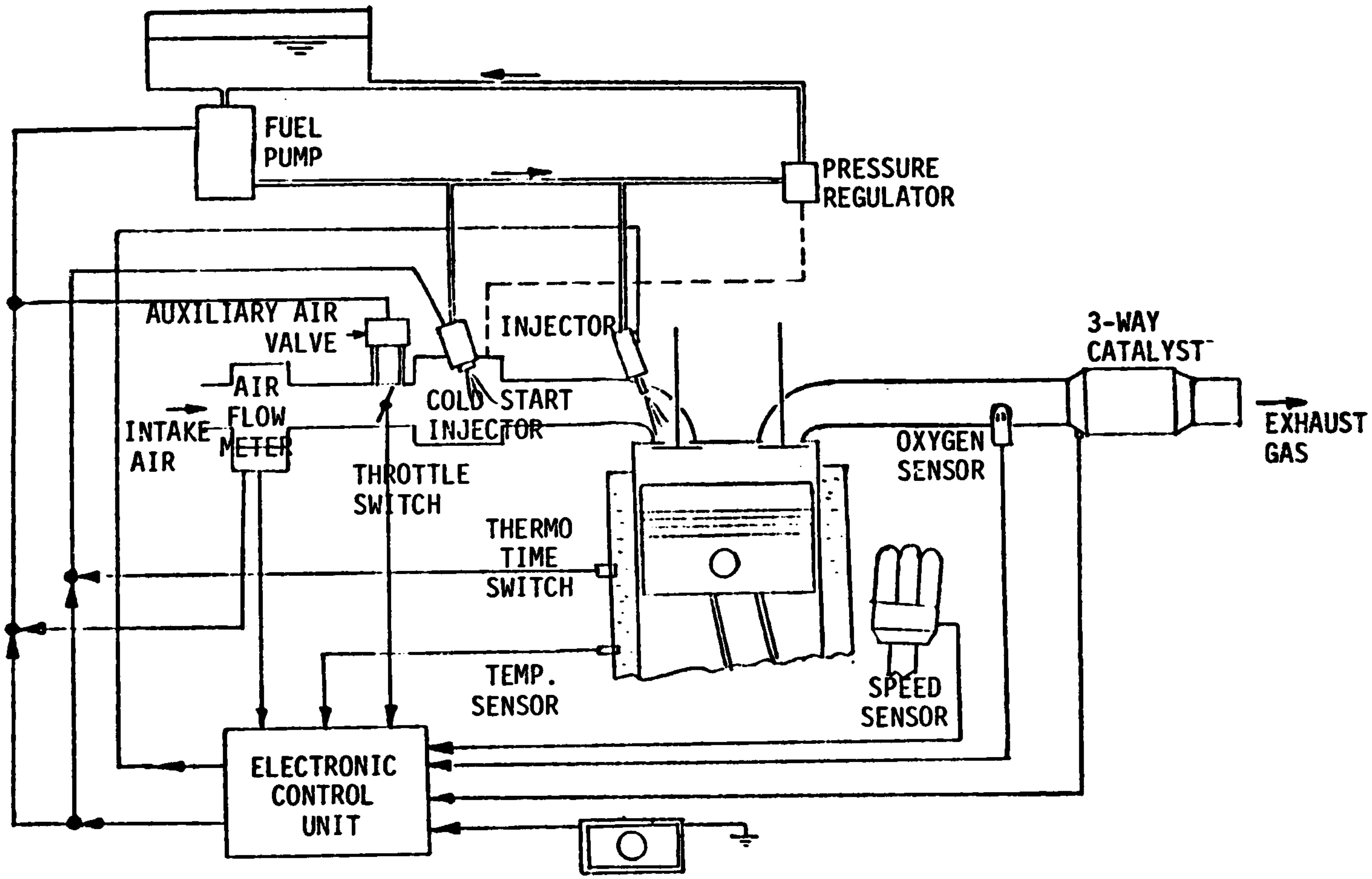


Figure 1. TYPICAL ELECTRONIC FUEL INJECTION (EFI) SYSTEM

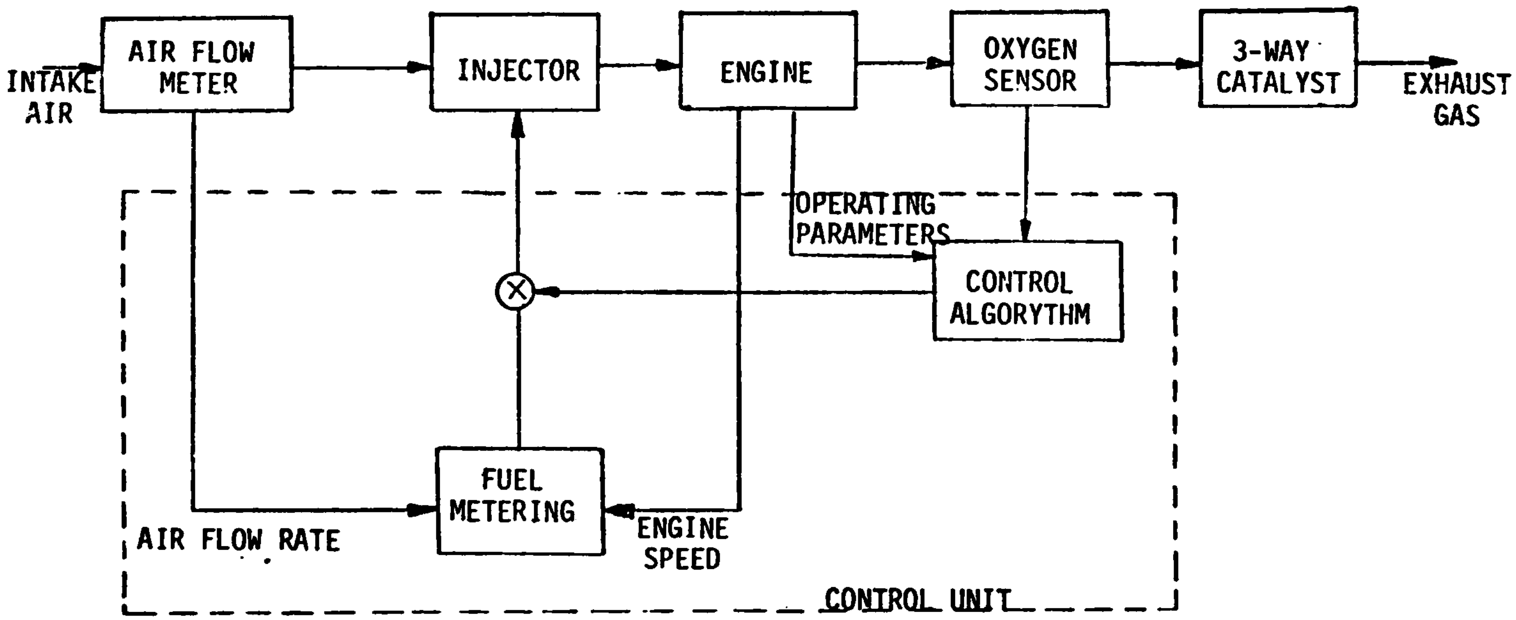


Figure 2. SIMPLIFIED BLOCK DIAGRAM OF EFI SYSTEM

2.3.1 Fuel Delivery Subsystem

The subsystem includes the fuel tank pick-up, an electric fuel pump, injectors for each cylinder, a fuel pressure regulator, supply and return line with a fuel filter. The fuel is held at a constant, low pressure (typically 2.5 to 3 bars) prior to the injectors and return to the tank at no pressure. As a result, cool fuel is delivered at all times during engine operation and formation of vapor bubbles in the fuel circulation system is prevented.

The solenoid-operated fuel injectors are installed in the intake manifold and spray fuel in front of the intake valves. Injection of fuel can be timed to take place for a group of injectors in order to reduce equipment costs. The amount of fuel delivered for each camshaft revolution can also be divided into two or more pulses to improve the uniformity in the distribution of the fuel mixture. For example, Bosch EFI-L system for 4-cylinder engines combines all four injectors into one single group and delivers two pulses of fuel injection for every camshaft rotation.

Since the fuel pressure is maintained constant, the flow rate and the stroke of the injector valve stem is also constant (approximately 0.15 min.), the fuel delivery rate per injection is thus controlled by the valve opening duration which is determined by the electronic control unit as a function of engine speed and air flow rate.

A separated injector is installed at the common intake manifold for cold start purposes. It has a swirl type nozzle for better fuel atomization and delivers extra amounts of fuel to enrich the mixture for easy starting. A thermo-time switch can be utilized to control the duration during which the start valve is switched on depending on the engine coolant temperature. This prevents the wetting of the spark plugs with a rich starting mixture.

2.3.2 Air-Induction Subsystem

This subsystem includes the integrated intake manifold, throttle-body assembly for primary air control, and an auxiliary air valve controlled by water temperature and supplies additional cold-start air.

Air flow measurements can be accomplished by sensing the throttle valve position, intake air pressure and temperature. The signals are input to the electronic control unit for air flow calculations.

An advanced air-flow meter has been developed by Bosch (References 18 and 19). The meter is located at the upstream side of the throttle valve as illustrated in Figure 1. One advantage of this system over the previous one is that, if necessary, the exhaust gas recirculation (EGR) can be incorporated without effecting the air flow measurement.

2.3.3 Primary Sensors

There are five primary sensors: (a) An engine speed sensor is usually mounted integral with the distributor. It provides the electronic control unit with data on engine speed for air flow calculations and engine phasing data for synchronizing injector-open timing. (b) An intake manifold pressure sensor measures absolute pressures in the intake manifold to provide for continuous calculation of air flow to the engine. This pressure sensor is not required if a separated air-flow meter is employed. (c) Throttle-position sensor provides both the absolute and rate of change of throttle-position needed for fuel-injection control. It senses closed-throttle, part-throttle, or wide-open throttle and conveys this information to the electronic control unit for electronic processing. (d) Three temperature sensors measure the intake air, engine coolant and catalytic converter temperature. An intake air temperature sensor is used in combination with the intake manifold pressure transducer to precisely determine the density of the inducted air. An engine coolant temperature sensor is mounted in the coolant passage and is needed for control of fuel enrichment, EGR cut-off or injection during cold operation. A temperature sensor is also mounted in the catalytic converter to control engine cold-start operation to accelerate catalyst warm-up period. (e) An oxygen sensor is mounted

in the exhaust manifold and measures oxygen concentration in exhaust gases. The output signal from this probe is used to regulate precisely the air/fuel mixture and makes it possible, together with the catalytic converter, to lower the noxious exhaust emissions. The most common oxygen sensor is a galvanic device with a zirconium dioxide solid electrolyte and a porous platinum electrode.

2.3.4 Electronic Control Unit (ECU)

The ECU is the heart of an EFI system. It receives information from the sensors that monitor key engine operating parameters; it processes this information using a selected control logic and computes the exact fuel requirement relative to air flow; it transmits electric pulses to the solenoid-operated injector valves. If necessary, the unit can also control EGR and other special operations, such as ignition advance. The current ECU utilizes integrated circuit to the greatest possible extent and has demonstrated excellent reliability.

Recent developments on the microprocessor based, electronic engine control system (Reference 23) may offer a better performance and economic tradeoff of alternate design approaches in the 1980's. This will increase the degree of freedom and accuracy of engine control and further improve the engine performance. However, many development efforts are needed to make it a reliable product in the harsh environment of the automotive application. It is considered to be premature to be implemented into the present hybrid vehicle demonstration program.

3.0 ON/OFF OPERATING MODE

The heat engine for a hybrid vehicle will be frequently on or off at a relatively high speed (1200-1500 rpm) at wide-open throttle as opposed to a conventional heat engine which starts at low idle ($\sim$600 to 800 rpm). The frequent on/off mode will be a new experience for heat engine development. Some considerations on this unusual operation are discussed as follows.

3.1 Start-Up

Two basic approaches can be adopted for controlling engine on/off operation: use of an engine clutch or a valve deactivation.

3.1.1 Mechanical Clutch

Use of a clutch represents the simpler approach of the two. The clutch engages or disengages the engine with the rest of the drive train during engine on or off cycle, respectively. The maturity and the availability of the component makes it attractive. However, several problem areas could be associated with this operation. First, since the engine will be turned on at a high speed, the vehicle at the instance of clutch engagement may experience a rough transition of speed due to the difference in engine speed and that of the drive train. A control system to improve the drivability will have to be developed. Secondly, each time the engine is started, there may be a short period of metal-to-metal contact of the connecting rod and main bearing. This may reduce bearing life somewhat. An auxiliary oil pump and modified bearing design have been suggested (Reference 24) to alleviate this problem.

3.1.2 Valve Deactivation

The valve deactivation approach, on the other hand, does not have the two problems discussed above. Valve deactivators (valve selectors) were developed for cylinder cut-out (terms such as engine limiting or variable displacement engine are also used) applications (References 27-29). The concept is to cut-out a number of cylinders from operation from a multi-cylinder engine, such as a V-8, when the full power from all cylinders is not needed. This allows fewer cylinders to operate at near the wide-open throttle and minimize the engine fuel consumption. While cylinders are not firing, a significant

amount of pumping work is required to overcome the throttling losses across the intake and the exhaust valves. With valves being closed, the engine needs only to overcome the friction loss. Figure 3 shows the test data of motoring work for a typical V-8 and small L-4 engines. It is seen that with the intake and the exhaust valve deactivated, the motoring work to run an inactivated engine can be reduced to an acceptable level.

Incorporating valve deactivators, a hybrid vehicle engine will be at identical speeds as the drive train at all times regardless whether the engine is on or off. Drivability of the vehicle will not be penalized due to frequent on/off operation of the engine and the engine lubrication can be ensured.

The hardwares of the valve deactivators have been well-developed for larger size engines (V-8 and 2.1L Pinto L-4) and their reliability demonstrated (References 28 and 29). Figure 4 illustrates the hardware design and its operation. Cost of adding valve deactivators for all cylinders is compatible with that of a clutch. The developed hardwares are, however, only applicable to engines having rocker arms in the valve train.

For smaller size engines with overhead cams and no rocker arms, new designs and developments of a valve deactivator will be required. One feasible design is shown in Figure 5. This is a modified version from that developed by Eaton Corporation (Reference 29) which is designed to be installed on the rocker arm studs. When the upper and lower body projections are "in-phase" as shown in Figure 5, the upper and the lower bodies of the valve deactivator become one integral part and valve motion follows the cam profile. As the solenoid is energized, it rotates the upper body during the time when the cam is at its base-circle and forces the upper and lower body projections to be "out-of-phase". Body projections thus will be allowed to move along the mating slots. The relative motions between the upper and the lower body permit the cam shaft to continue its rotation while the valves are deactivated. This mechanism requires only slight modification from the existing Eaton's hardware. Its development is considered to be of no major problem. Considering possible problems which may occur in the on/off operation with the clutch, it is recommended that valve deactivation be considered for the near-term hybrid vehicle.

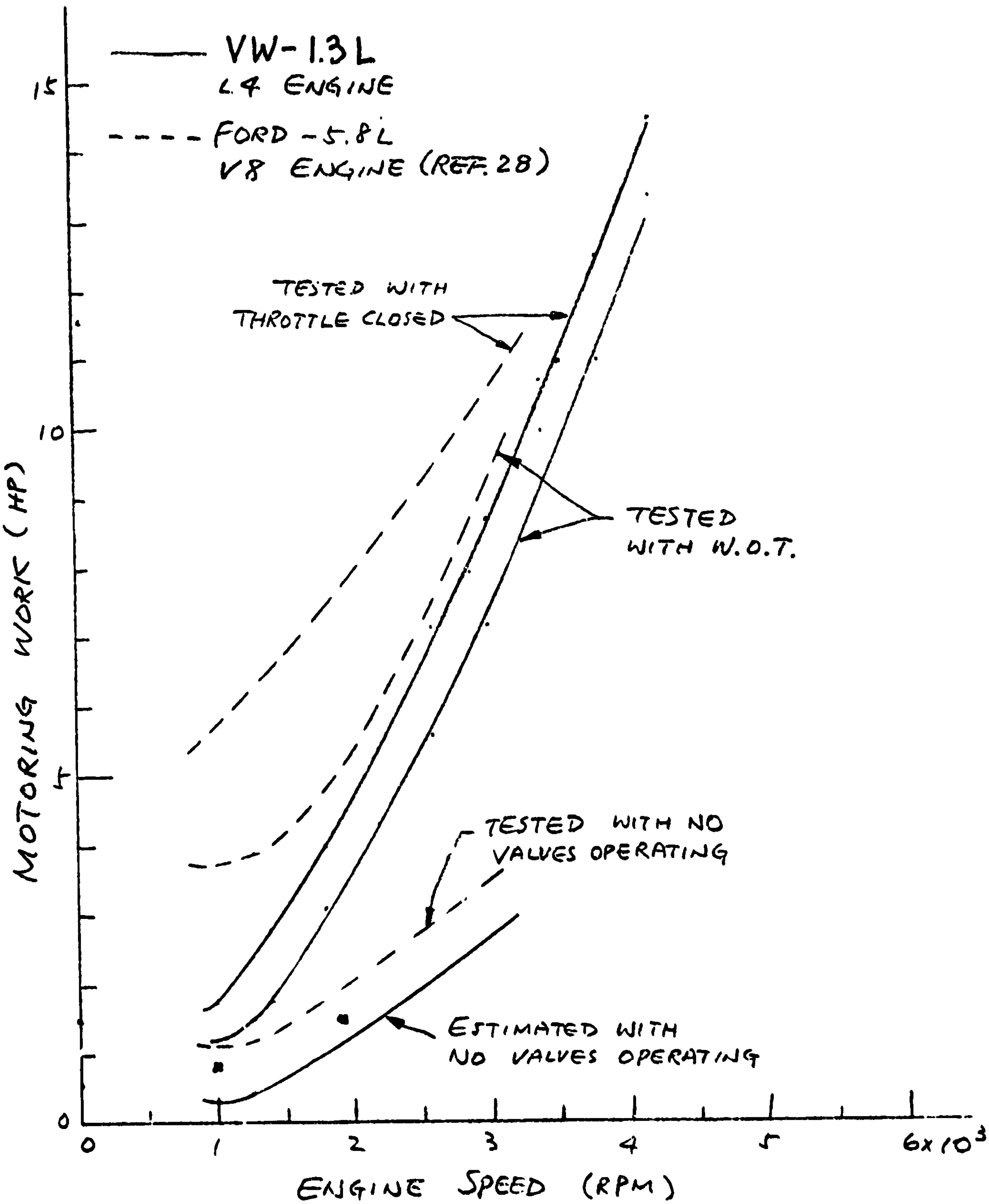


FIG 3. MOTORING WORK

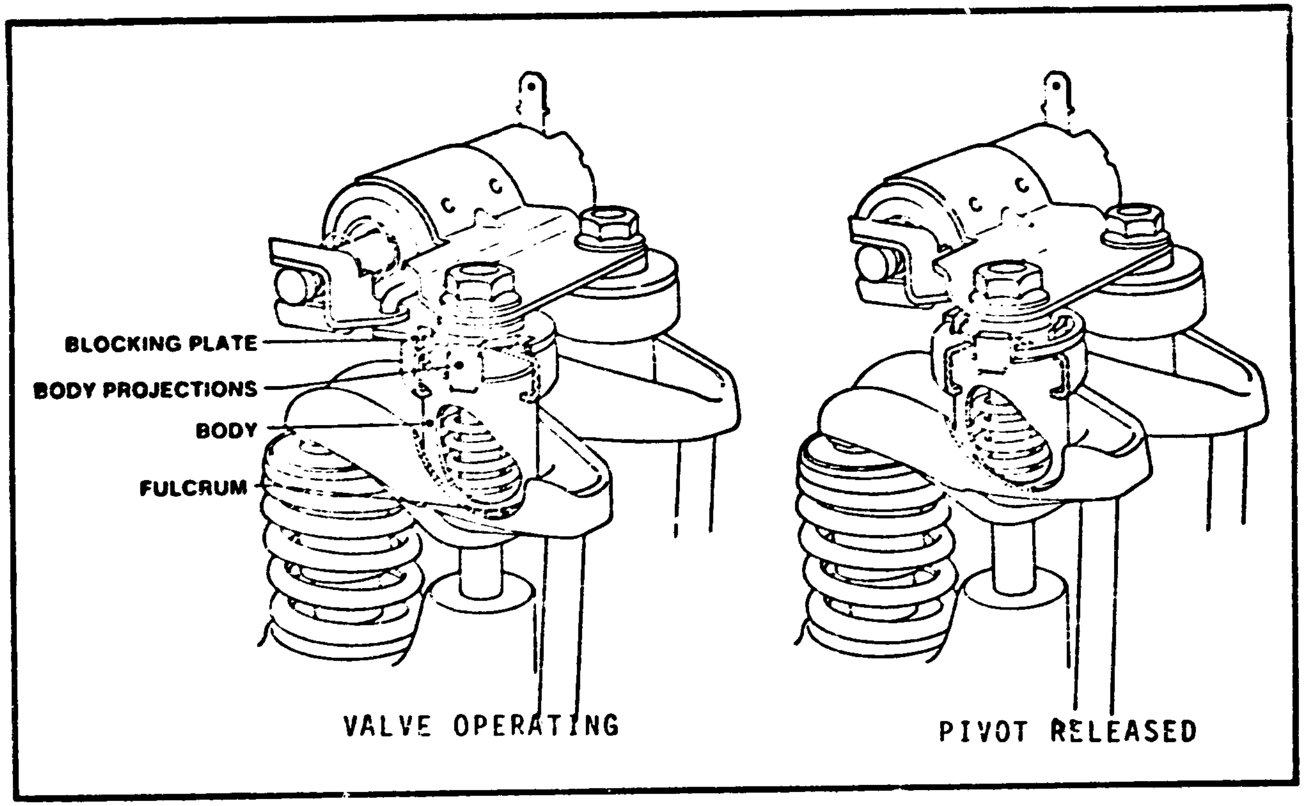
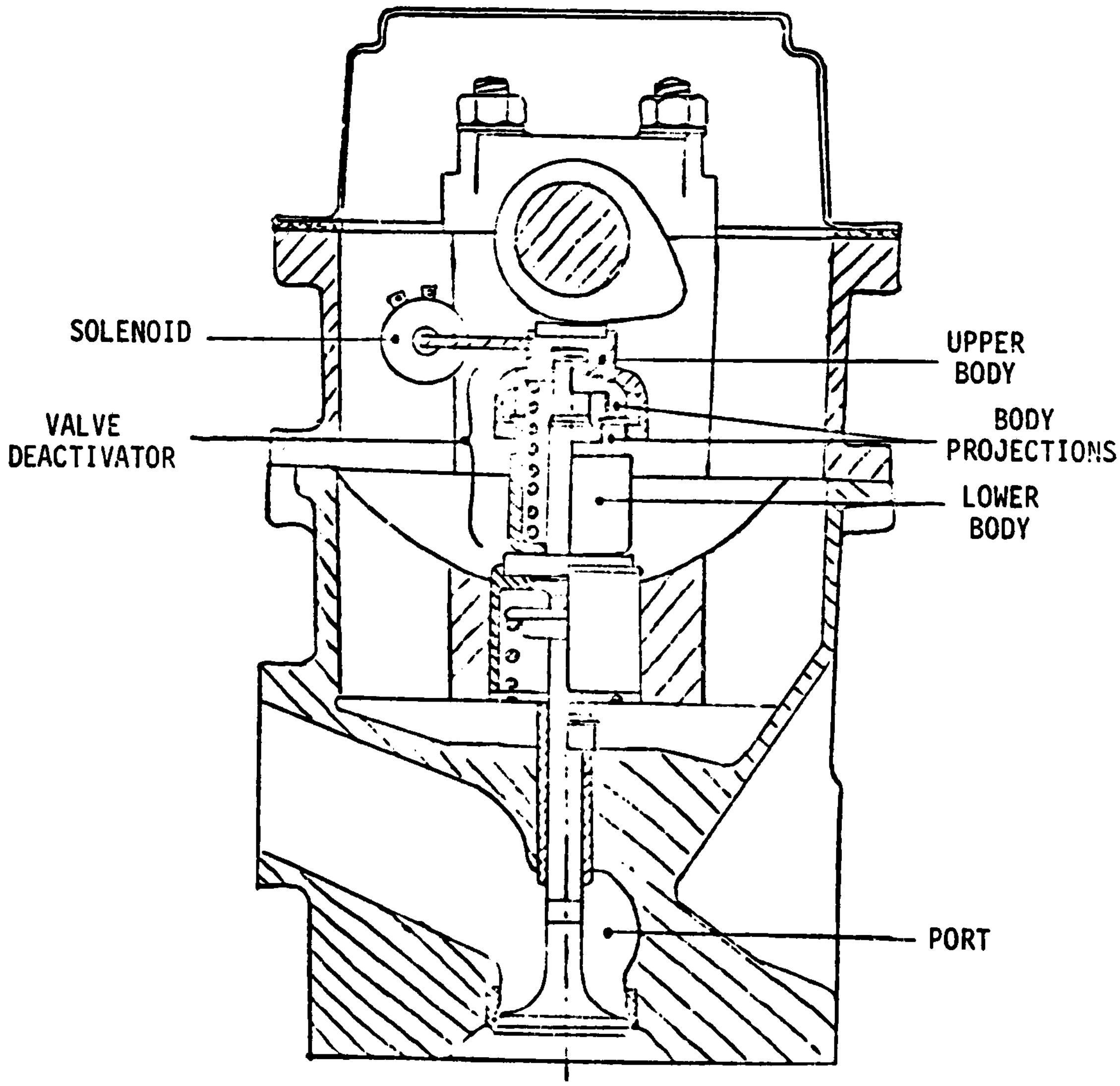


Figure 4. EATON'S VALVE SELECTOR MECHANISM (Reference 29)

Figure 5. VALVE DEACTIVATOR



The sequence for turning the engine on is as follows. First, the intake and the exhaust valves are activated as the vehicle speed exceeds the desired level (e.g. 30 mph). After additional full crank revolutions, solenoids for the fuel injections are energized to start the normal operation.

3.2 Fuel Cut-Off

As has been discussed previously, fuel delivery will be cut-off during vehicle deceleration and as the vehicle is at low speed (below 30 mph). The fuel injection should be terminated before the valve deactivation takes place. To avoid misfire or fuel rich for any one of the cylinders, the fuel cut-off and valve deactivation sequence should be carefully monitored. Figure 6 illustrates one of the fuel cut-off techniques.

The example given in Figure 6 is for a four-cylinder, four-stroke engine. Fuel injections are delivered twice per engine operating cycle (720° crank angle). For each cylinder valves are deactivated at least two full crank revolutions after the fuel is cut-off. This ensures that complete combustion will take place at every cylinder and prevent any unusually high unburnt hydrocarbon emission.

3.3 Emissions

3.3.1 Steady State

Several investigations have been conducted relating to the effect of on/off operation for hybrid vehicles on their exhaust emission levels. (References 25, 26, 30 and 31). The effect of a hybrid operation on vehicle emissions depends on the operating characteristics of the system and the emission characteristics of the engine and its emission control strategies. Nevertheless, the hybrid vehicle, compared to its conventional counterpart, showed substantial reductions in both unburnt hydrocarbons and carbon monoxide emissions. This is due to the elimination of engine idling and low load operations. However, the oxides of nitrogen emission tends to increase slightly for hybrid vehicles using a smaller engine than a conventional one. Again, this is due to the wide-open throttle operation for a hybrid system. Table 3 shows the potential emission reductions of hybrid systems from the conventional counterparts as reported by some earlier studies (References 30 and 31).

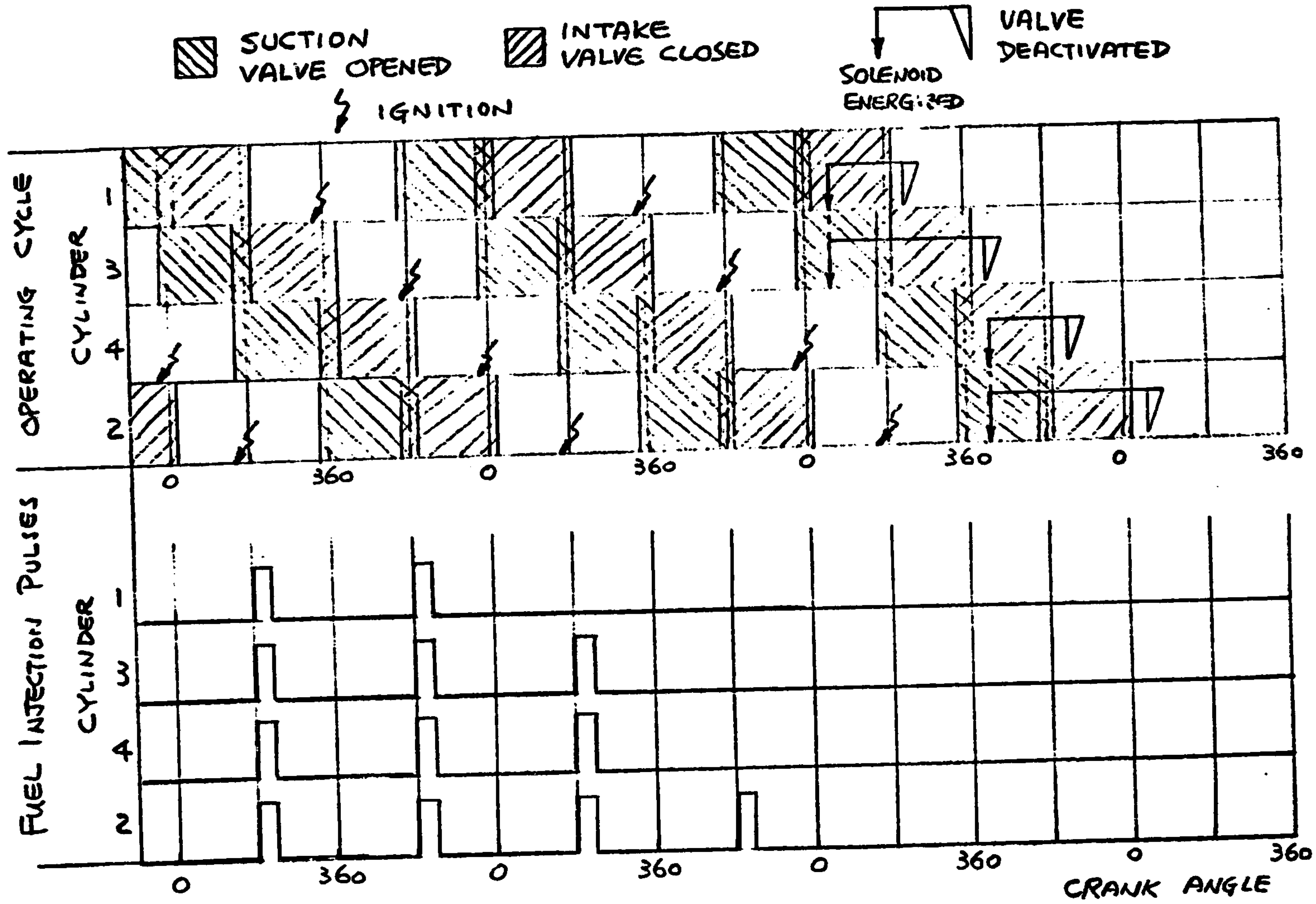


FIG. 6 FUEL CUT-OFF SEQUENCE FOR A EFI-ENGINE WITH VALVE DEACTIVATION

Table 3. POTENTIAL EMISSION REDUCTION OF HYBRID VEHICLES

Changed From Conventional Vehicle (Based on GM/MILE)

	UHC	CO	NO_x
Reference 30	-76%	-40%	+17%
Reference 31	-65%	-40%	+30%

For an existing EFI engine using a three-way catalyst, the emission levels are significantly below the 1981 Federal standard as indicated in Table 2. Use of this system for the hybrid application will likely meet the emission requirements. Incorporation of more complicated emission controls, such as the exhaust gas recirculation (EGR), retarding ignition timing, two-stage catalyst and air-injection (References 32-35), are not considered to be necessary at the present time, but can be added to the engine if need arises in the future.

3.3.2 Catalytic Converter

The three-way catalytic converter proves to be the most effective way developed so far to reduce the toxic emissions below the regulating levels. In order to achieve high conversion efficiencies for all HC, CO and NO_x emissions, the air/fuel ratio must be controlled in the vicinity of stoichiometrics. Figure 7 shows typical emission-reduction characteristics of the three-way catalyst. As indicated, the equivalence ratio, λ, (A/F / A/F of stoichiometrics) must be maintained within a narrow bend of 0.995 to 1.003 in order to achieve 85% or better conversion efficiencies for all three emissions. This accurate control of air/fuel ratio has been demonstarted with the electronic fuel injection system with an oxygen sensor feed-back from the exhaust as discussed in Section 2. Detailed discussions of the catalyst are also given in several publications (References 36-39).

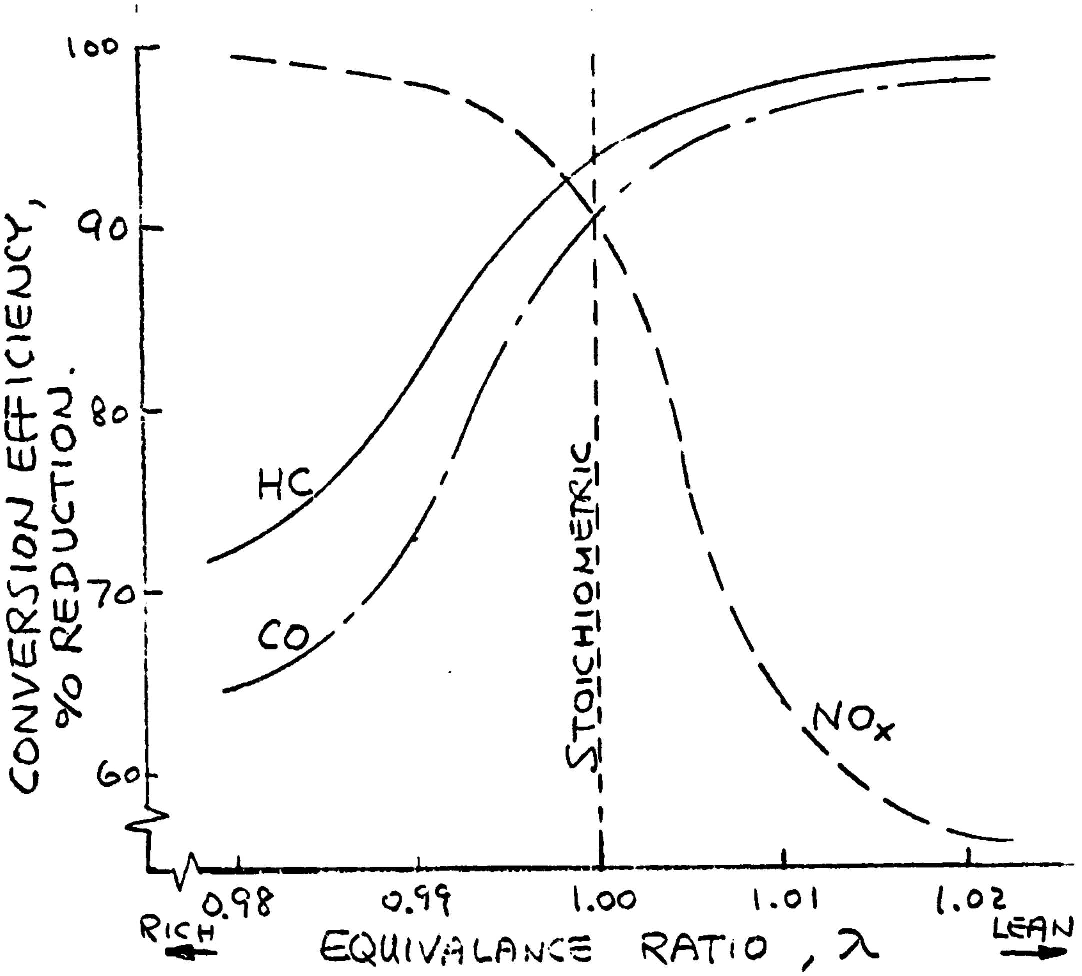


FIG. 7 3-WAY CATALYST CHARACTERISTICS

Discussion with Matthey Bishop, Inc. personnel has concluded that for a 1.6 little engine, the catalyst should be sized in the order of 100 cubic inches. No major problems are foreseen for hybrid on/off operations. However, the following concerns should be investigated during future testing.

Durability due to the thermal "shock" in frequent on/off operation.

Proper insulation of the catalyst material to reduce temperature variation and use of a metal support of the catalyst material (References 38 and 39) can alleviate this problem.

Cold start.

Catalyst will be effective only after it exceeds approximately 600°F. In addition to several alternate approaches which will be discussed in the following section, the metal supported catalyst also offers a faster warm-up period for the catalyst.

Oven temperature.

In case of misfire or extreme fuel rich operations, catalyst material may be damaged if the temperature exceeds 2500°F. With accurate fuel injection controls using EFI and the fuel cut-off strategy described in Section 3.2, this problem should be minimal.

3.3.3 Cold Start

In some conventional vehicles, over 50% of the total HC/CO emissions are produced during the first several minutes of urban driving cycle tests while the engine is still cold (Reference 35). For a hybrid vehicle the engine will be turned on only at high speed and wide-open throttle, cold start HC/CO emission will probably be less severe. However, means to control this high HC/CO emission should still be investigated.

At cold start both the oxygen sensor and the catalyst are ineffective. A swirl-type cold start injector and hot-spot in the intake manifold should be incorporated to promote fuel atomization and vaporization. Fuel enrichment and spark retardation can be utilized to provide fast warm-up of exhaust gas. Preheat systems at the intake manifold and exhaust system, which are heated with the battery electric power, will accelerate warm-up of air, exhaust gas and catalyst material. Since production of cold start HC/CO is a complicated

phenomeon and no accurate analytical tool is available to carry out a reasonable prediction, development of cold-start emission control should be conducted during the actual test.

3.3.4 Fuel Cut-Off

Even though some HC spikes may be anticipated during the fuel cut-off, testing conducted by Ford (Reference 28) did not indicate any noticeable increase in total HC emission with accurate electronic fuel control.

3.4 Mechanical Effects

The four areas which will be considered are structural effects, wear characteristics, noise and thermal effects, all of which are affected to some degree by the change in speed range and engine on/off operating mode, while the increased number of start-ups influences only wear.

The structural loading of the reciprocating elements of an internal combustion engine consists of a combination of the cycle combustion pressure induced forces and the acceleration loads of the elements. Since only small variations in pressure occur due to speed variation, and since the acceleration loads increase as the square of the speed, these inertia forces will be significant in this discussion. The design of the reciprocating elements is based on a cyclic life requirement, and is generally predicated on fatigue loading and characteristics. The effect of cycle forces is even further reduced since the contribution is basically a compression stress in the elements (above top dead center where forces are highest) and fatigue is primarily associated with tension stresses.

The data shown in Figure 8 for a typical material indicates that fatigue properties are fairly constant for a life greater than one million cycles, which is less than one percent of the design life of a typical automobile engine. It is thereby unlikely that the hybrid engine's operating speed range will have any impact on the design of these elements, since their design always accommodated operation at full speed for a finite portion of engine life, and the flatness of fatigue allowables indicates little, if any, changes in design would be necessary.

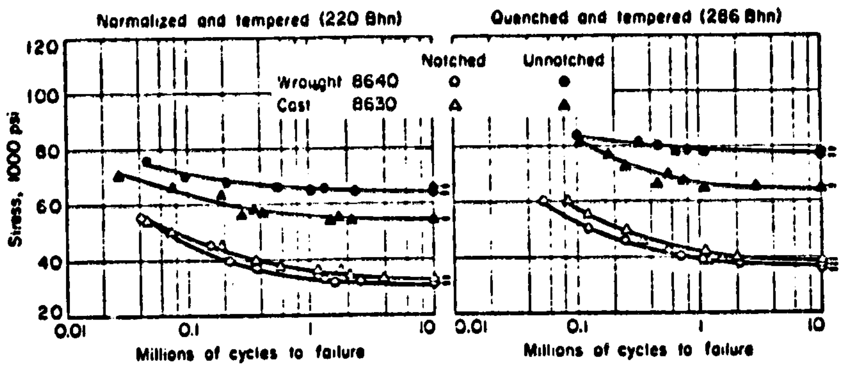


Figure 8. CYCLIC FATIGUE STRESS

The crankshaft, cam shaft, flywheel and other rotating members are subjected to tensile stresses through bending and/or centrifugal force, both of which are speed related. Again, however, the flatness of the fatigue curves and reduced number of cycles provide design adequacy.

The engine bearings are designed to satisfy operation over a range of operating speeds, but the most severe operation occurs during start-up, before an oil film can be established and when metal-to-metal contact initially exists. Hydrodynamic bearing design is simplified as the operating speed range is reduced. Problems with whirl are reduced and bearing geometry can be optimized to enhance bearing life. The significant number of start-up cycles could conceivably create a wear problem, however, since metal-to-metal contact can occur without the hydrodynamic film effect. If a problem is encountered, solutions include:

- A hydrostatic system utilizing either a separate oil pump or pressurized container to be used only at start-up.
- Incorporation of rolling element bearings.
- Incorporation of improved wear characteristic bearing materials.
- Redesign of bearings to extend capability.
- Adopt valve deactivation techniques to maintain engine shaft rotation.

The noise problem of the hybrid engine will be attributable to the wide-open throttle operation or high engine speed to charge the battery at low vehicle speed if it is needed. The road noises generally encountered along with high speed engine noise in common proportional systems tend to balance each other. Some methods of reducing this effect are to utilize the reduced speed range to advantage by providing improved mechanical balancing and damping systems, tuning of the circulation systems to optimize at the higher flow rates, and enhanced acoustic insulation.

The frequent on/off engine operation introduces more cyclic thermal variation of the engine parts. Similar to the cyclic fatigue characteristics of a conventional engine design which falls at the flat portion of the fatigue curves, it is believed that additional thermal cycles in hybrid applications will not require substantial design change. However, to minimize the thermal cyclic effect and improve cold-start capability and emission characteristics for the next engine on-cycle, the fan and water pump can be turned off during the engine off cycle.

4.0 SELECTION AND CHARACTERIZATION OF HYBRID VEHICLE ENGINE

4.1 Selection of the Engine

Based on the tradeoff studies discussed above, it is concluded that an EFI engine combined with a three-way catalyst appears to be the best candidate heat engine system for the near-term hybrid vehicle. As shown in Table 2 of Section 2.1, EGR alone will be unable to reduce the nitrogen oxides emission below the 1980's regulatory level without severe penalty on engine performance. Since NO_x level for a hybrid vehicle is expected to be higher than a conventional counterpart, as discussed in Section 3.3.1, use of a three-way catalyst presents a logical choice.

One existing EFI engine in the size of 60 to 80 HP is a 97 CID, L4 VW engine. The engine specifications are listed in Table 4 for reference. A smaller engine is also made available by VW in Europe. It is a 4-cylinder, 80 CID, EFI engine delivering 61 HP at 6000 rpm.

TABLE 4. ENGINE SPECIFICATIONS FOR VW 97-CID (1.6 L) ENGINE

Number of Cylinders	4
Bore	3.366"
Stroke	2.717"
Displacement	96.66 in^3
Compression Ratio	8:1
Cylinder Head Type	Overhead Cam
HP at Engine Speed	75 at 5800 rpm
Torque at Engine Speed	73 ft-lbs at 3500 rpm
Fuel System Type	EFI
Maximum Air Flow	98 CFM
Emission Control	EGR/OXI. CAT.

4.2 Engine Characteristics

Using an EFI and the feed-back control from the oxygen sensor at the exhaust, a remarkable control of air/fuel ratio can be accomplished. Figure 9 shows the equivalence ratio operated in a VW-1.6 L engine. The air/fuel ratio can be practically controlled within 1% of the stoichiometric ratio. Fuel enrichments are incorporated in this engine at the wide-open throttle (WOT) and idling conditions for extra power requirements. For hybrid vehicle this fuel enrichment is not considered to be necessary except during the cold-start condition. Figure 10 is the performance map for the same engine. As can be seen, the best engine efficiency occurs approximately at 94% throttling-opening at mid-speed range. As the fuel enrichment at WOT is eliminated, the best engine efficiency will take place at WOT. Thus, if a hybrid vehicle using a VW-1.6 L engine is operated between 1500 and 4200 rpm and 90% to 100% throttle openings, the engine efficiency throughout the operating range can be maximized.

Table 5 lists the performance and emission characteristics at various speeds and loads of the VW-1.6 L engine. All emission data shown is the measurement without the catalytic converter. When a three-way catalyst is used, based on the catalytic conversion efficiencies shown in Figure 7, reductions of the HC, CO and NO_x emissions should be 94, 91 and 90%, respectively. It is also noted that high CO and low NO_x emissions at full load (WOT) conditions are due to the fuel enrichment incorporated in this engine.

For the smaller VW-1.3 L (80 CID) engine, similar engine characteristics are found. Figure 11 shows the performance map while Table 6 lists the performance and emission data.

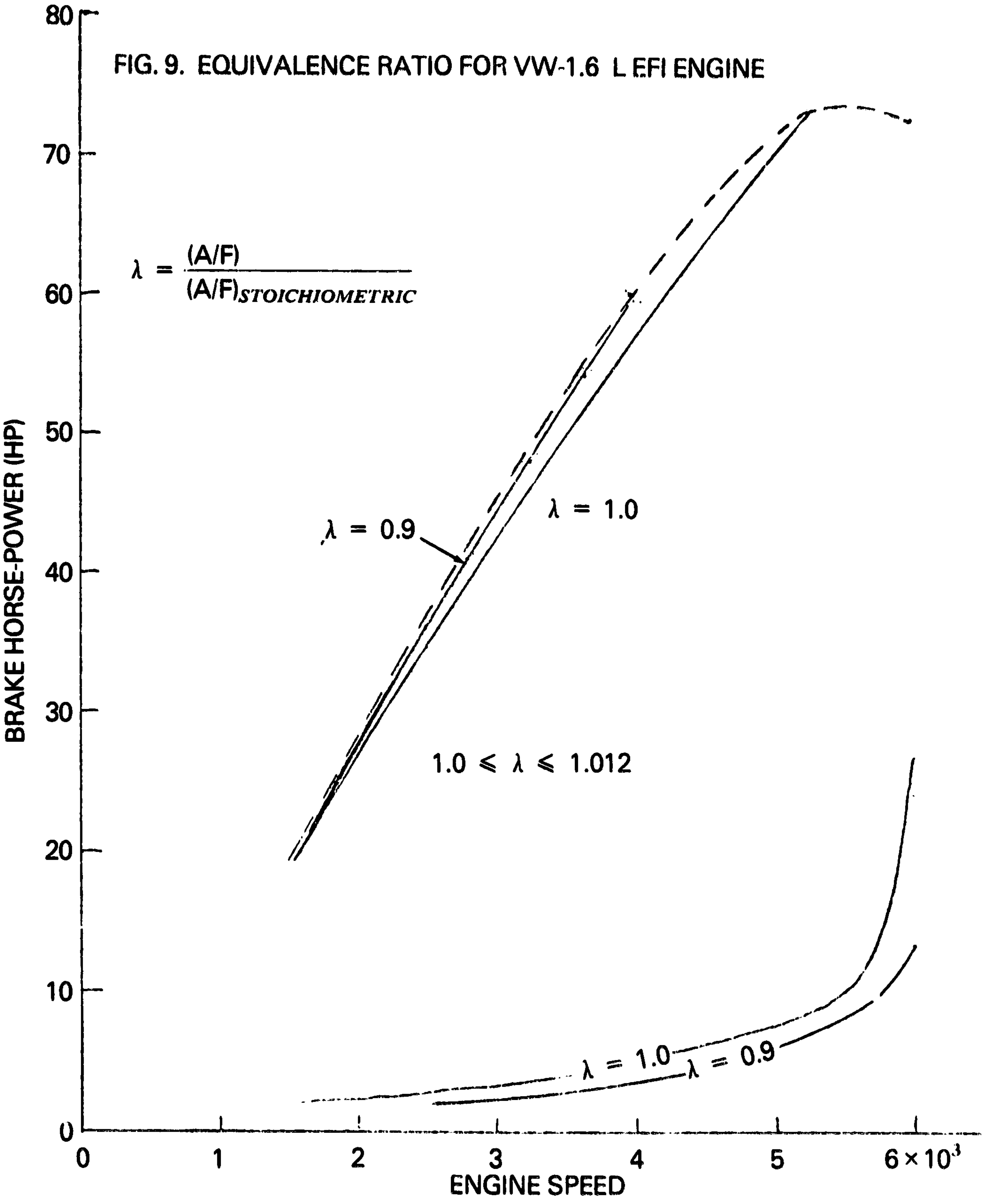


FIG. 9. EQUIVALENCE RATIO FOR VW-1.6 L EFI ENGINE
$\lambda = \frac{(A/F)}{(A/F)_{STOICHIOMETRIC}}$
$\lambda = 0.9$
$\lambda = 1.0$
$1.0 \leqslant \lambda \leqslant 1.012$
$\lambda = 1.0$
$\lambda = 0.9$
BRAKE HORSE-POWER (HP)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6×10^3
ENGINE SPEED

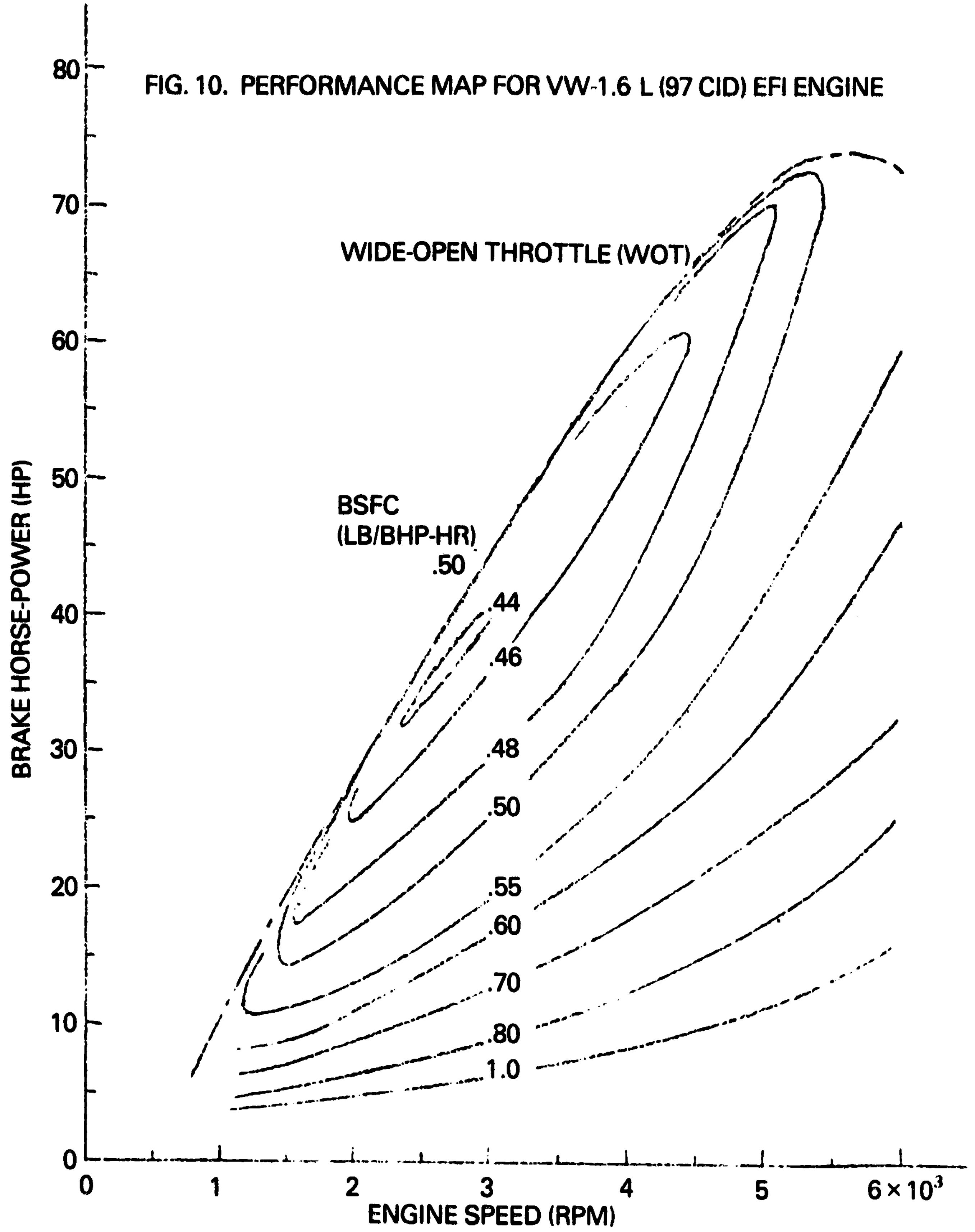


FIG. 10. PERFORMANCE MAP FOR VW-1.6 L (97 CID) EFI ENGINE
WIDE-OPEN THROTTLE (WOT)
BSFC
(LB/BHP-HR)
.50
.44
.46
.48
.50
.55
.60
.70
.80
1.0
BRAKE HORSE-POWER (HP)
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6 × 10³
ENGINE SPEED (RPM)

Table 5. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.6 L ENGINE

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 1200 RPM					
14	100	.605	256	3.68	.83
14	97	.521	29.8	2.1	8.64
11.8	84	.528	15.5	1.78	8.28
9.5	66	.566	15.6	1.87	5.71
7.1	50	.646	17.7	2.03	4.01
4.7	34	.882	23.4	2.24	2.89
2.3	16	1.48	43.5	2.93	2.64

* All emission data before catalyst

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 1600 RPM					
21	110	.575	223	3.24	1.0
18.9	100	.476	17.6	1.75	9.58
15.8	84	.486	16.8	1.71	8.0
12.6	67.6	.524	17.4	1.82	6.89
9.5	50	.560	17.7	2.17	5.79
6.	34	.759	24.5	2.55	4.0
3.1	16	1.327	38.7	3.14	2.87
0	0				

* All emission data before catalyst

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 2000 RPM					
28	119	.512	142.5	2.79	3.14
27.5	116	.446	16.8	1.81	12.9
23.7	100	.474	19.7	1.94	12.1
19.7	84	.495	18.9	1.98	11.06
15.8	66	.521	18.0	2.26	11.4
11.9	50	.579	17.7	2.31	8.9
7.9	34	.743	23.4	2.65	6.42
3.9	16	1.12	32.8	3.33	4.2
0	0				

* All emission data before catalyst

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 2400 RPM					
34	119	.510	125	2.73	4.65
33	116	.447	16.7	1.94	14.9
28.4	100	.461	17.3	1.93	14.1
23.7	84	.496	20.7	2.05	13.2
19	67	.513	20.7	2.37	13.4
14.2	50	.595	22.7	2.56	11.1
9.4	34	.727	24	2.73	8.5
4.7	16	1.189	37	3.4	6.17
0	0				

* All emission data before catalyst

Table 5. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.6 L ENGINE (continued)

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 2800 RPM					
41	123	.519	144.0	2.88	4.2
38.6	116	.445	15.3	1.99	15.5
33	100	.463	16.2	1.75	14.5
27.6	84	.495	18.0	1.98	13.5
22	66	.513	20.4	2.18	14.05
16.6	50	.582	23.1	2.49	11.63
11	34	.715	26.7	2.69	7.27
5.5	16	1.112	36.4	3.4	7.09

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 3200 RPM					
48	128	.513	139.0	2.56	5.0
44	117	.452	14.9	1.77	17.3
38	100	.472	15.8	1.95	16.18
31	84	.493	17.5	2.13	15.45
25	66	.533	20.3	2.27	16.44
19	50	.588	24.5	2.47	14.16
12.6	34	.720	29.6	2.81	11.67
6.2	16	1.110	41.0	3.48	9.52

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 3600 RPM					
54.2	126	.497	118.1	2.19	6.49
49.7	116	.447	15.9	1.43	17.46
42.6	98	.467	15.8	1.72	16.90
35.7	82	.479	17.4	1.89	16.02
28.4	66	.521	19.3	2.11	16.97
21.3	50	.597	23.5	2.19	15.68
14.2	32	.75	32.5	2.62	12.75
7.2	16	1.194	46.9	5.14	19.83

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 4000 RPM					
59.5	125	.493	99.2	2.07	8.7
55.3	116	.452	15.4	1.52	18.7
47.5	100	.467	16.2	1.66	17.82
39.4	82	.492	16.6	1.85	18.02
30.8	66	.525	17.9	2.81	19.32
23.1	50	.605	23.2	2.34	18.25
15.5	34	.742	28.8	2.52	15.7
7.4	16	1.219	47.7	3.24	13.9

* All emission data before catalyst

Table 5. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.6 L ENGINE (continued)

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 4600 RPM					
66	120	.510	97.5	1.95	10.74
63.4	116	.468	14.4	1.48	22.11
54.4	98	.485	15.7	1.62	21.1
45.3	82	.507	17.2	1.77	20.32
36.2	66	.550	18.2	1.99	22.76
27.9	50	.608	20.3	2.08	22.43
18.2	34	.765	27.0	2.42	21.7
9.1	16	1.179	45.5	2.93	19.3

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 5200 RPM					
72.8	117.6	.517	81.5	1.88	13.3
72	116	.487	14.7	1.37	22.97
61.6	98.5	.505	15.7	1.53	22.58
51	82	.526	17.0	1.67	22.45
41	66	.566	18.2	1.91	25.27
30.7	50	.630	20.2	2.02	24.76
20.5	32	.789	26.4	2.24	23.76
10.3	16	1.242	38.7	2.79	22.4

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.6 L (97 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 6000 RPM					
72.5	101	.531	15.7	1.34	23.56
71	100	.528	15.9	1.38	23.5
58	81	.561	18.1	1.59	23.07
46.7	65	.607	19.3	1.98	23.45
35.5	50	.679	23.4	2.03	25.72
24.1	34	.834	40.2	2.16	23.4
13.4	19	1.240	60.3	2.84	18.9

PERFORMANCE & EMISSION TEST DATA

ENGINE:

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR) * BSCO	BSHC	BSNOx
ENGINE SPEED =					

* All emission data before catalyst

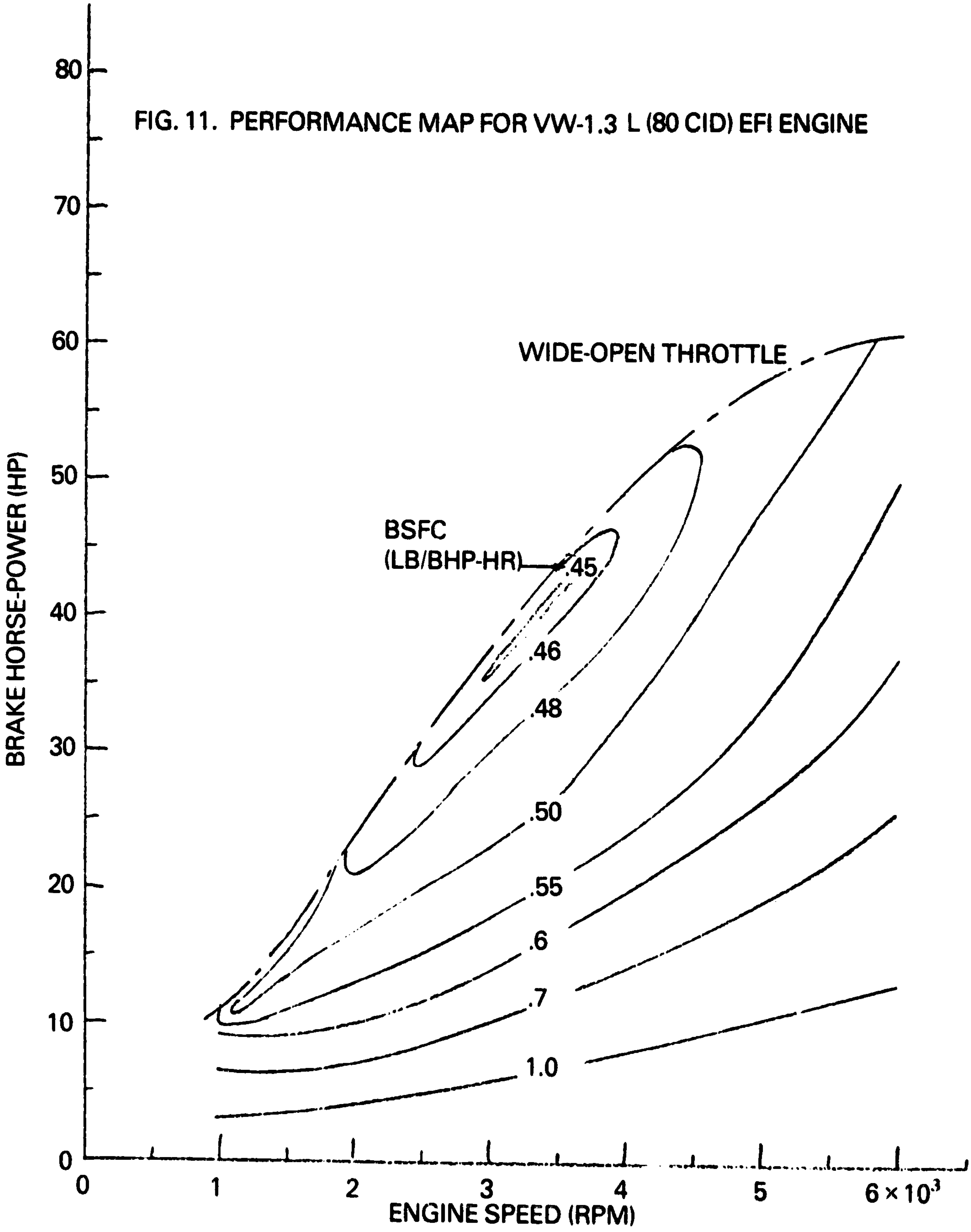


FIG. 11. PERFORMANCE MAP FOR VW-1.3 L (80 CID) EFI ENGINE

Table 6. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.3 L ENGINE

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 1200 RPM					
12.5	107	.53	53.6	3.72	8.4
11.7	100	.503	13.6	3.08	112.1
9.5	81	.568	15.3	2.94	9.66
7.1	62	.612	16.68	2.99	6.25
4.7	40	.821	23.8	3.28	3.98
2.1	19	1.59	56.67	5.06	3.66

* All emission data before catalyst.

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 1600 RPM					
16.9	108.8	.525	77.93	2.77	5.3
15.7	100	.509	16.27	2.25	9.55
12.6	81	.528	14.60	2.30	8.17
9.4	60	.618	17.13	2.71	6.29
6.3	40	.739	20.48	2.85	3.92
3.2	20	1.316	35.93	3.26	3.08

* All emission data before catalyst.

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 2000 RPM					
23.2	119	.476	46.1	2.44	9.16
19.7	101	.492	15.5	2.32	12.33
15.7	81	.515	17.0	2.33	10.64
11.8	60	.558	15.76	2.93	11.35
7.9	41	.653	18.59	3.31	7.54
4	20	1.108	31.0	2.79	3.25

* All emission data before catalyst.

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 2400 RPM					
28.3	122	.470	42.2	2.34	10.85
28.4	122	.466	25.28	2.32	12.43
23.7	101	.477	14.94	2.43	13.84
18.9	80	.503	16.72	2.54	13.4
14.2	60	.549	19.79	3.11	14.22
9.5	41	.619	19.05	3.47	11.62
4.7	20	1.047	30.0	3.60	4.82

* All emission data before catalyst.

Table 6. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.3 L ENGINE (continued)

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 2800 RPM					
34.6	126	.463	33.82	2.28	12.56
33.1	122	.458	15.47	2.07	15.29
27.6	101	.480	16.81	2.34	14.27
22.1	80	.508	17.42	2.78	15.29
16.6	60	.556	21.36	3.33	16.14
11.1	40	.621	21.13	3.66	13.67
5.6	20	.925	32.27	3.86	7.14

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 3200 RPM					
40.2	126	.471	39.55	2.50	11.7
37.9	122	.465	15.65	2.17	14.91
31.5	101	.493	17.17	2.07	14.19
25.3	81	.507	20.16	2.80	14.68
19.1	62	.555	23.67	3.14	16.02
12.3	40	.689	30.90	3.58	13.41
6.2	19	1.01	42.2	3.97	9.19

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 3600 RPM					
45.3	129	.460	52.2	2.80	10.1
43.1	122	.452	14.57	2.34	14.67
35.4	101	.479	16.57	1.95	13.53
28.4	82	.498	17.91	2.32	13.60
21.2	60	.563	20.66	2.96	16.60
14.4	41	.687	24.96	3.36	14.79
7.1	20	1.125	40.5	3.91	11.66

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 4000 RPM					
48.5	125	.476	54.74	2.72	10.06
47.5	122	.465	25.58	2.48	13.3
39.6	101	.484	14.75	2.07	13.51
31.5	82	.516	16.44	2.075	13.84
23.7	60	.547	18.51	2.90	17.17
15.9	61	.691	22.2	3.46	17.29
7.9	20	1.114	38.4	3.98	15.18

* All emission data before catalyst.

Table 6. PERFORMANCE AND EMISSION TEST DATA FOR VW-1.3 L ENGINE (continued)

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 4600 RPM					
53.8	121	.484	48.38	2.32	11.67
45.2	47.6	.493	16.23	2.0	15.07
36.3	82	.525	16.74	2.17	16.33
27.2	62	.566	19.74	2.76	20.07
18.2	41	.693	28.35	3.34	20.11
9.0	21	1.078	43.44	3.99	18.55

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSHC	BSNOx
ENGINE SPEED = 5200 RPM					
58.5	116	.487	23.69	2.07	16.10
51.2	101	.501	18.51	2.06	17.04
41.0	81	.530	15.33	1.79	13.77
30.8	62	.586	23.38	2.86	21.88
20.6	41	.697	31.75	3.44	22.09
10.3	21	1.095	47.28	4.34	21.84

PERFORMANCE & EMISSION TEST DATA

ENGINE: VW 1.3 L (80 CID) EFI

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR)* BSCO	BSCH	BSNOx
ENGINE SPEED = 6000 RPM					
61.1	106	.529	45.92	2.40	15.3
58.7	101	.531	39.6	2.26	16.29
47.7	82	.554	22.23	1.95	16.54
35.5	62	.615	28.98	2.64	19.44
23.9	41	.729	34.35	3.29	21.04
11.7	20	1.145	46.32	3.33	19.49

PERFORMANCE & EMISSION TEST DATA

ENGINE:

HP	BMEP (PSI)	BSFC (LB/BHP-HR)	EMISSIONS (GM/BHP-HR) BSCO	BSHC	BSNOx
ENGINE SPEED =					

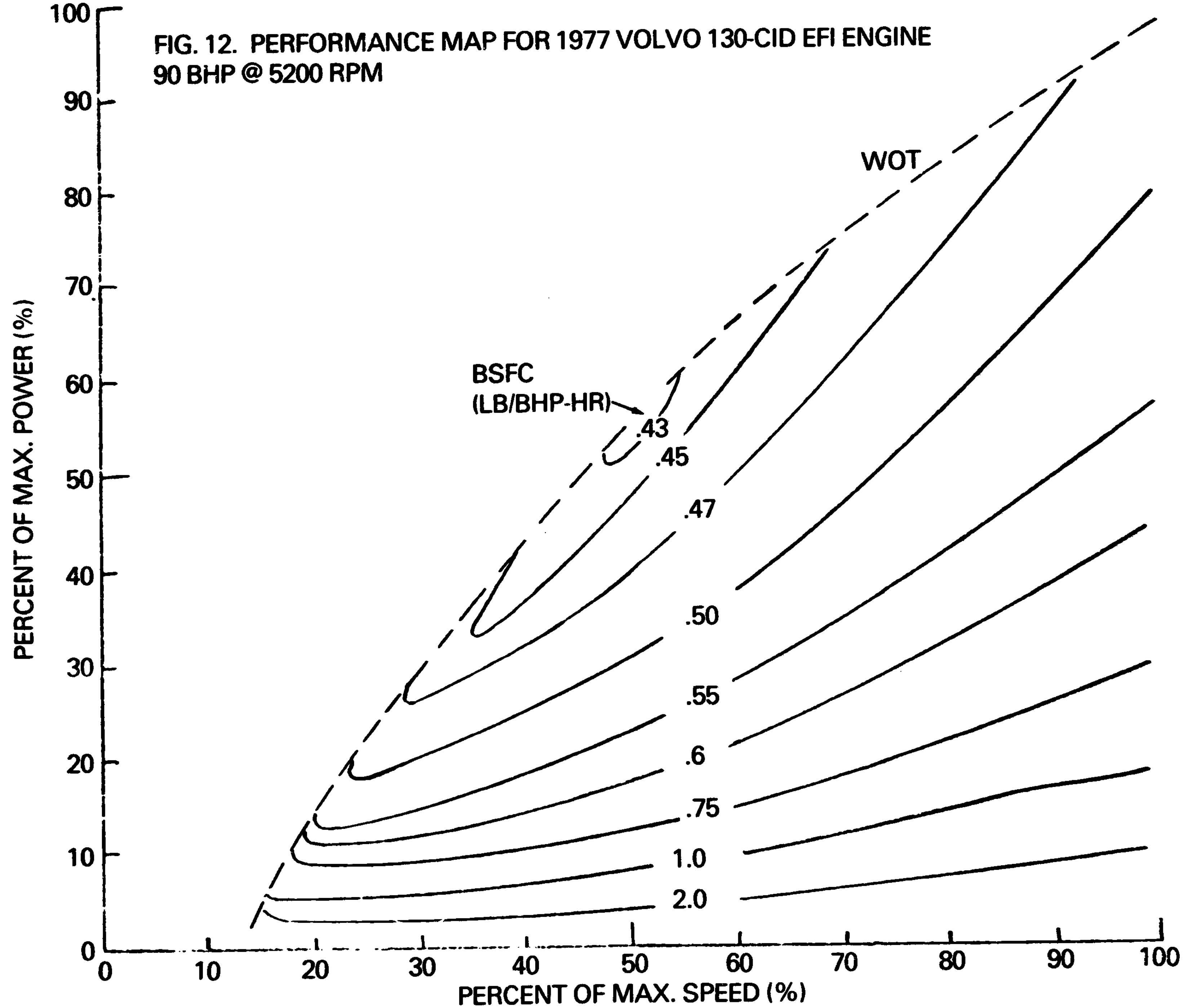
* All emission data before catalyst.

Even though the 130-CID Volvo engine (Reference 14) may be slightly oversized (90 HP at 5200 rpm) for the five-passenger hybrid vehicle, its characteristics offer several interesting comparisons with the smaller VW engines. Contrary to the VW engine, the Volvo engine does not implement fuel enrichment at WOT and idling. Also, instead of maintaining slightly lean mixtures ($\lambda > 1.0$) as shown in Figure 8, as in the VW engines, it maintains a slightly rich ($\lambda < 1.0$) mixture throughout most of the operating range. The range of the equivalence ratio is $0.995 \leq \lambda \leq 1.001$. As a result, the Volvo engine has its best engine efficiency at WOT as shown in Figure 12.

The slightly better engine efficiency for the Volvo engine is attributed to a slight advance of ignition timing. At 2500 rpm and full load, for instance, the ignition timing is 28° BTDC as opposed to 25.6° BTDC for VW 1.6 L engine.

Operating at slightly rich mixture also offers an advantage of lower NO_x emission. Figure 13 shows the comparison of specific emission levels before catalyst at 2500 rpm engine speed. The Volvo engine produces lower NO_x emission than the VW. After the three-way catalyst, all three emissions are substantially reduced. Table 7 lists the Volvo engine emission levels after the three-way catalyst. Figures 14, 15 and 16 are the emission maps superimposed on the performance map for BSCO, BSHC and $BSNO_x$, respectively. As can be seen, operating at WOT not only offers a better fuel economy, but also results in lower combined emissions in general.

FIG. 12. PERFORMANCE MAP FOR 1977 VOLVO 130-CID EFI ENGINE
90 BHP @ 5200 RPM



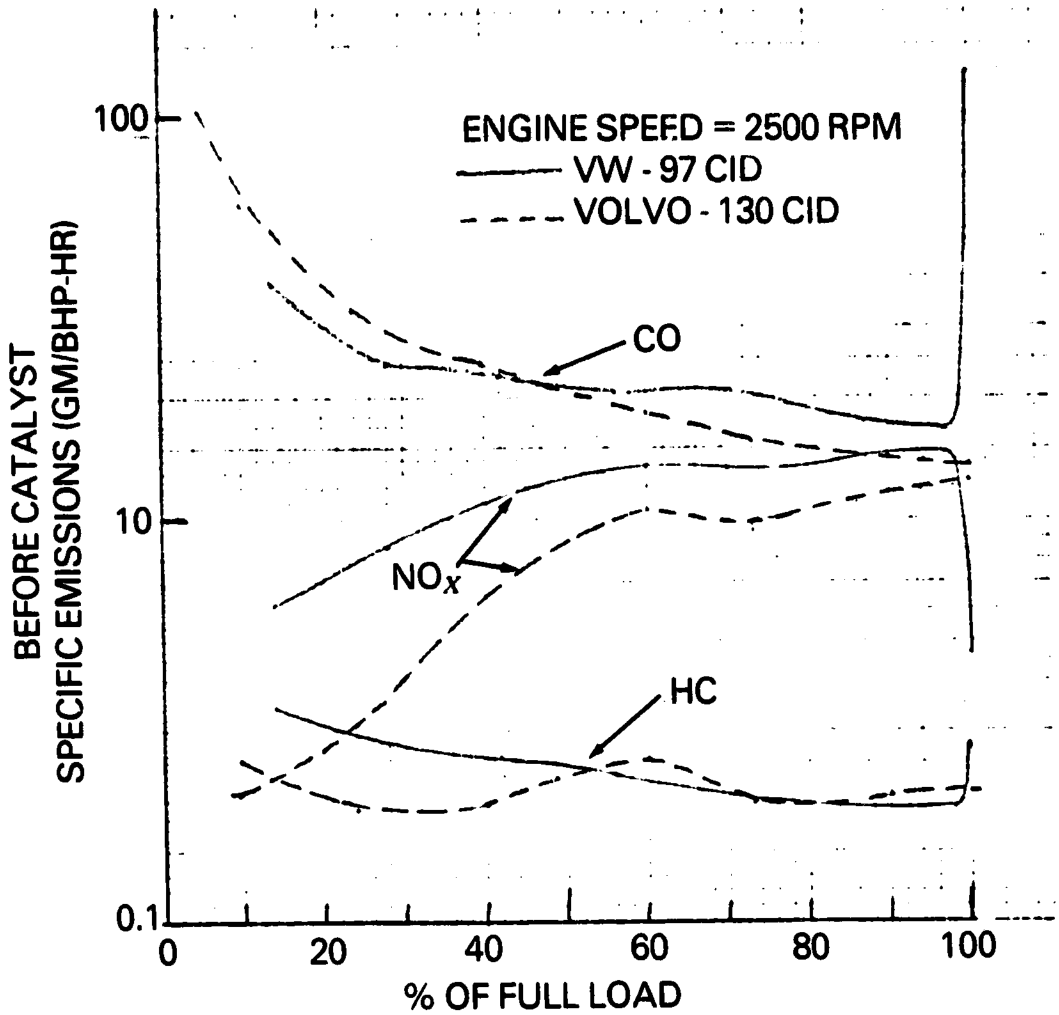


FIG. 13. COMPARISON OF EMISSIONS BETWEEN VW & VOLVO ENGINES

Table 7. PERFORMANCE AND EMISSION TEST DATA FOR VOLVO 130 CID ENGINE

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 900
FULL LOAD POWER (HP): 5.2

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.865	.096	.173	.327
90				
75				
60				
50	1.384	.308	.115	.308
40				
25				
10	7.5	12.5	9.2	0
0	32	13	17	1

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 1200
FULL LOAD POWER (HP): 18.2

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.505	2.2	.33	.176
90	.482	1.12	.226	.152
75	.522	1.15	.184	.044
60	.551	2.47	.211	.037
40	.819	.875	.139	.028
25	1.133	1.956	.2	.022
10	2.222	.555	.277	.11
0	8.0	10	.333	.667

ENGINE: VO 130 CID
ENGINE SPEED (RPM): 1500
FULL LOAD POWER (HP): 24.9

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.462	2.55	.24	.136
90	.473	1.77	.223	.076
75	.492	1.89	.16	.064
60	.487	.953	.133	.047
40	.64	.58	.14	.03
25	.828	2.61	.171	.034
10	2.04	8.75	.333	.042
0	3.5	3.167	.666	.166

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 1800
FULL LOAD POWER (HP): 32.1

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.461	1.28	.14	.096
90	.448	1.41	.165	.093
75	.479	1.49	.157	.083
60	.518	1.97	.196	.0825
40	.586	2.92	.226	.047
25	.75	4.1	.225	.025
10	1.844	22.6	.656	.0625
0	5.0	70.2	1.9	.18

Table 7. PERFORMANCE AND EMISSION TEST DATA FOR VOLVO 130 CID ENGINE (continued)

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 2300
FULL LOAD POWER (HP): 42

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.445	1.86	.144	.066
90	.449	1.615	.112	.096
75	.471	1.188	.118	.089
60	.494	.835	.136	.096
40	.572	1.53	.108	.072
25	.731	3.05	.183	.086
10	1.575	5.2	.3	.075
0	4.0	16.0	.667	.2

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 2500
FULL LOAD POWER (HP): 48.9

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.425	2.01	.127	.063
90	.432	1.5	.105	.07
75	.455	1.03	.133	.06
60	.469	.541	.109	.058
40	.541	1.765	.127	.066
25	.672	3.07	.147	.057
10	1.286	4.02	.204	.061
0	2.296	12.3	.346	.077

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 3400
FULL LOAD POWER (HP): 64.0

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.450	2.68	.153	.3
90	.455	2.37	.128	.172
75	.475	1.97	.098	.138
60	.496	1.264	.142	.075
40	.576	1.813	.14	.0545
25	.731	2.625	.119	.05
10	1.444	7.14	.19	.079
0	2.7	5.2	.233	.1

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 4000
FULL LOAD POWER (HP): 72

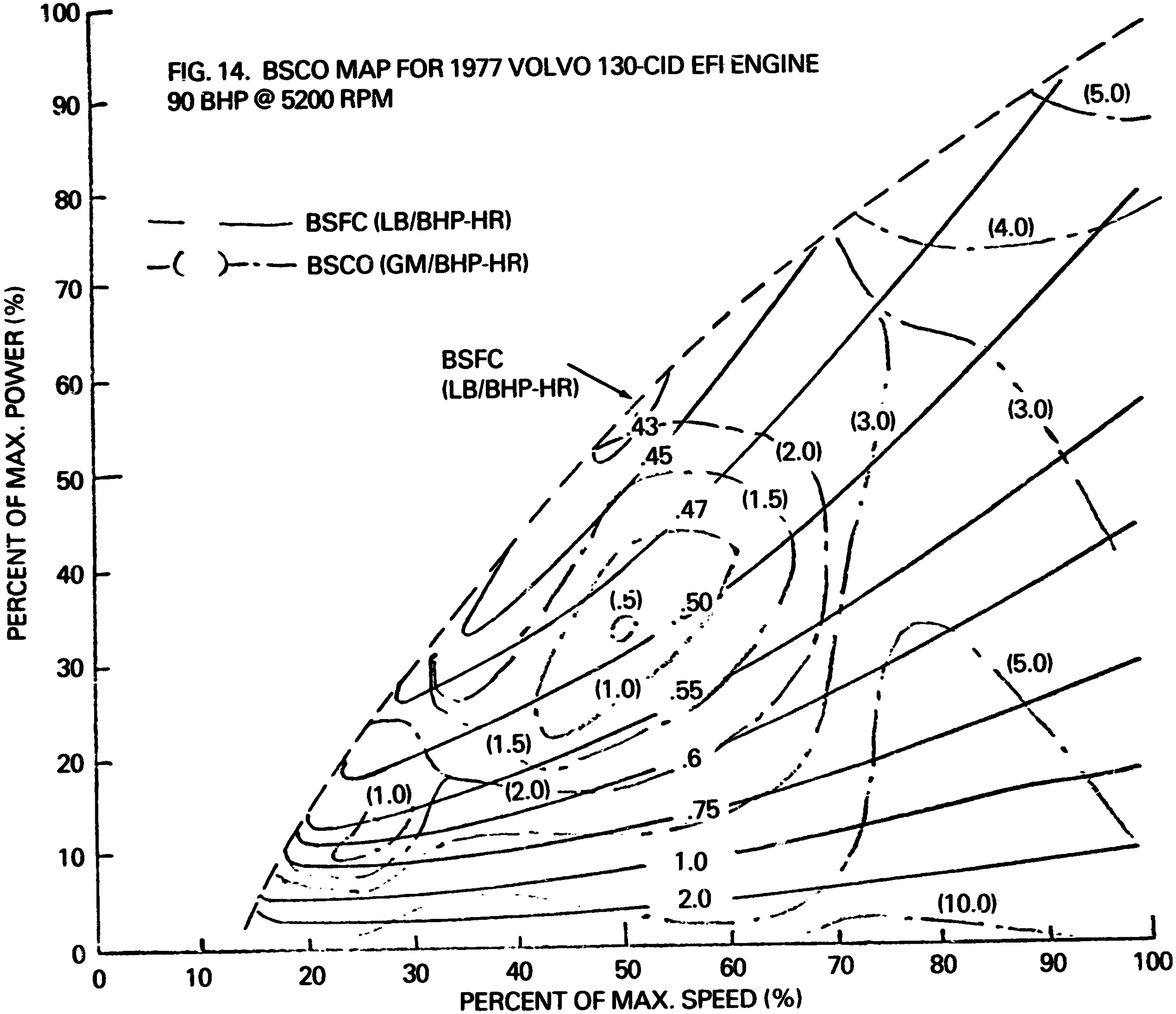
% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR) BSCO	BSHC	BSNOx
100	.458	4.16	.153	.28
90	.468	3.71	.154	.214
75	.493	3.44	.118	.155
60	.517	4.8	.196	.1085
40	.597	5.55	.191	.08
25	.768	5.66	.166	.061
10	1.438	7.0	.174	.087
0	2.310	10.45	.214	.119

Table 7. PERFORMANCE AND EMISSION TEST DATA FOR VOLVO 130 CID ENGINE (continued)

ENGINE: VOLVO 130 CID
ENGINE SPEED (RPM): 5200
FULL LOAD POWER (HP): 89

% LOAD	BSFC (LB/BHP-HR)	EMISSIONS (gm/BHP-HR)		
		BSCO	BSHC	BSNOx
100	.476	6.76	.361	.591
90	.491	4.98	.195	.441
75	.510	3.82	.134	.431
60	.542	3.1	.103	.404
40	.662	2.335	.166	.231
25	.844	3.03	.133	.107
10	1.652	5.36	.213	.112
0	2.185	7.23	.277	.169

FIG. 14. BSCO MAP FOR 1977 VOLVO 130-CID EFI ENGINE
90 BHP @ 5200 RPM



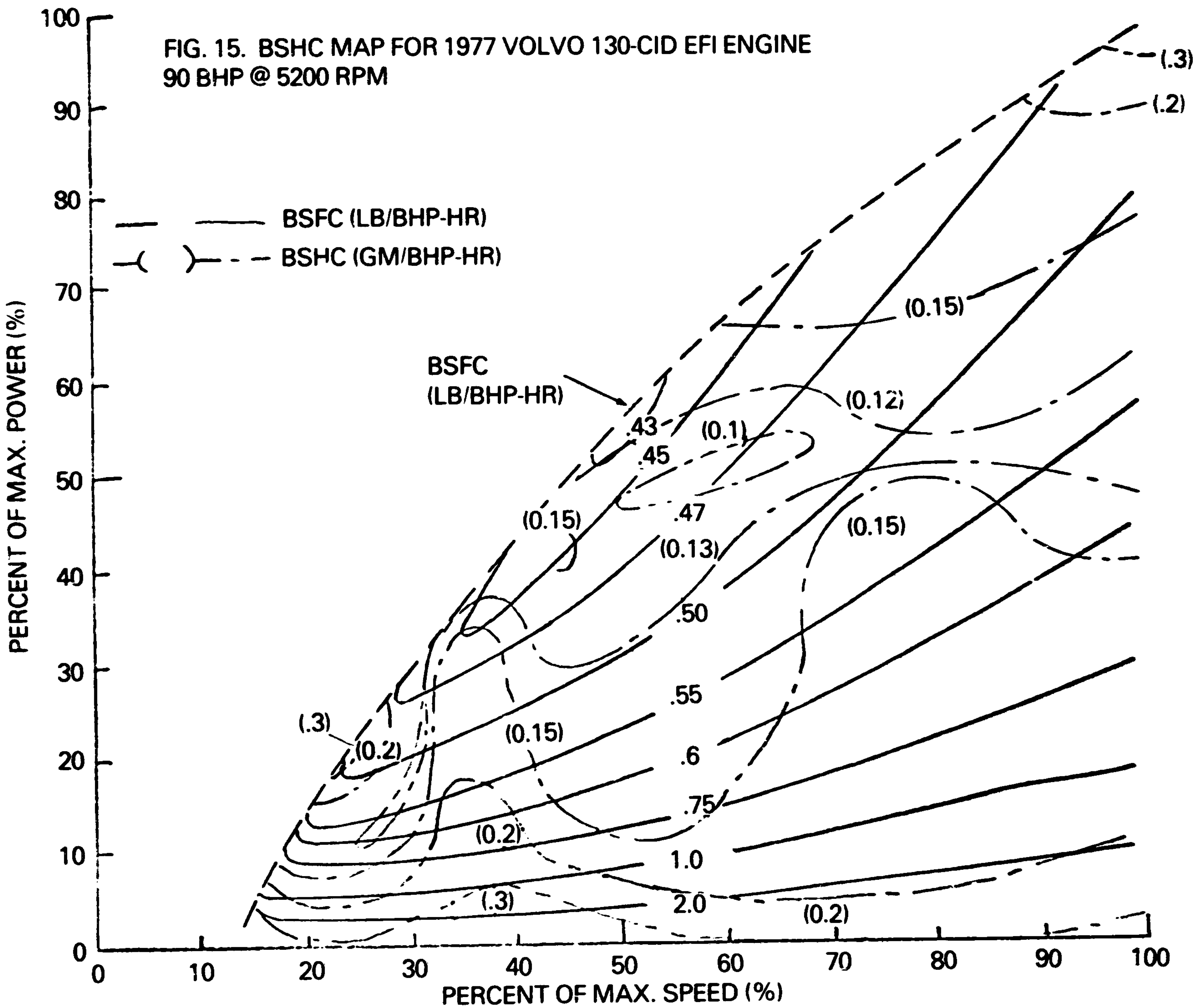


FIG. 15. BSHC MAP FOR 1977 VOLVO 130-CID EFI ENGINE
90 BHP @ 5200 RPM

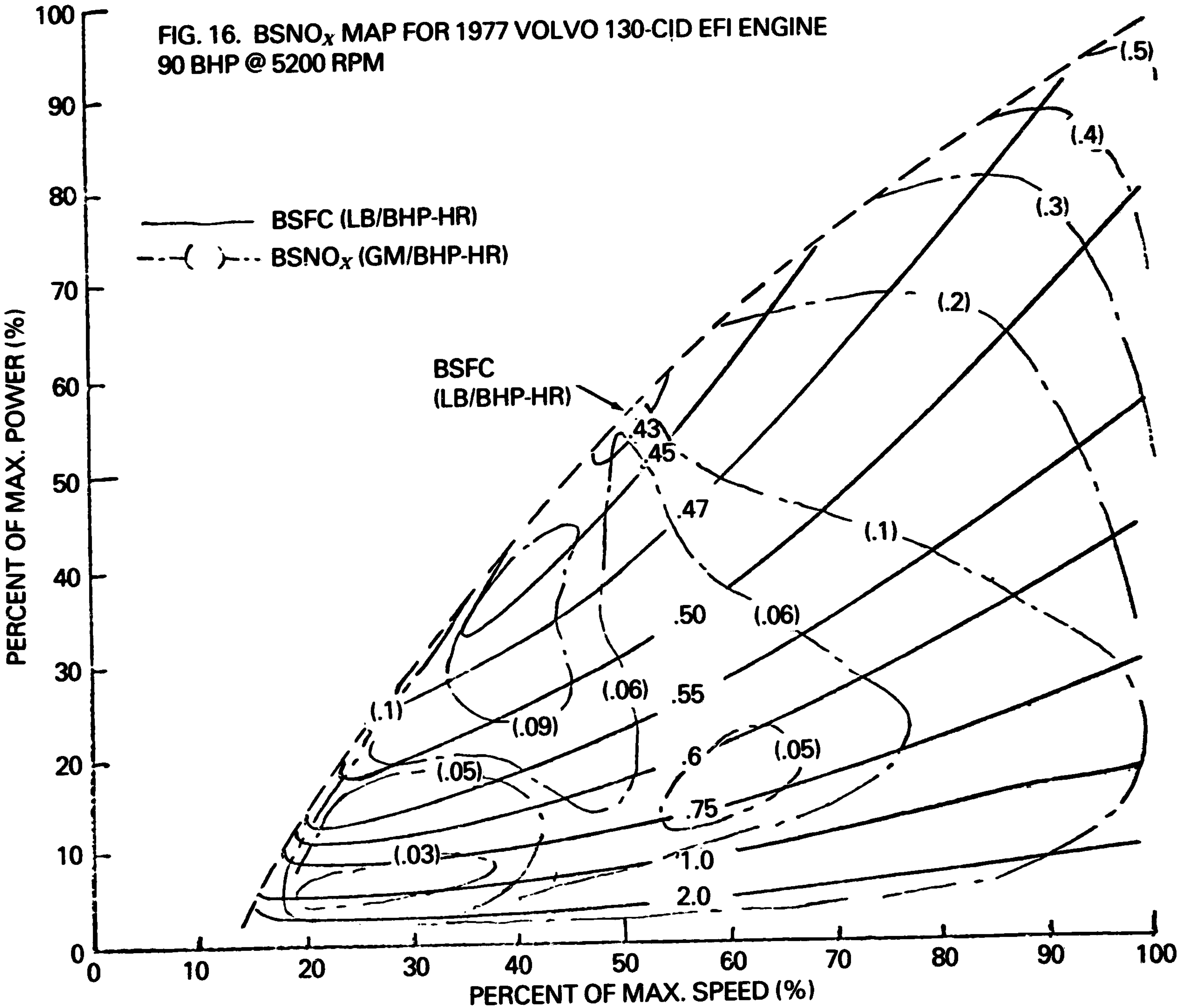


FIG. 16. BSNO$_x$ MAP FOR 1977 VOLVO 130-CID EFI ENGINE
90 BHP @ 5200 RPM

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Section 2

ASSESSMENT OF BATTERY POWER SOURCES

WORK STATEMENT

ESB Technology Company
Yardley, PA 19067

INTRODUCTION

Contract No. 955190 between California Institute of Technology Jet Propulsion Laboratory and General Electric Company covers a program entitled "Phase I of the Near-Term Hybrid Passenger Vehicle Development Program" under which studies shall be conducted leading to a preliminary design of a hybrid passenger vehicle that is projected to have the maximum potential for reducing petroleum consumption in the near-term (commencing in 1985). Effort under Contract 955190 is being conducted pursuant to an Interagency agreement between the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) and in furtherance of work under Prime Contract NAS7-100 between NASA and the California Institute of Technology. This work statement covers battery technology under General Electric Purchase Order A02000-220267.

SCOPE OF WORK

In support of General Electric Corporate Research and Development's work under Contract 955190, the Subcontractor shall furnish the necessary personnel, materials, services, facilities, and otherwise do all things necessary for or incident to the performance of the following tasks.

1. Provide consultation, as requested, on lead-acid batteries, such as:
   - Review of weight, size, performance characteristics of batteries based upon ISOA development program
   - Provision of cost estimates for such batteries in production quantities
   - Provision of estimates of cycle life of such batteries as a function of depth of discharge
2. Review prospective performance capabilities, cost and state-of-the-art of other promising battery types and recommend which one of them would appear to be the most suitable for use in the hybrid vehicle program. (It is recognized that considerable judgement must go into this recommendation, with some risk for error.) Provide the rationale for this recommendation.
3. Provide estimates of performance characteristics for the battery system recommended in Item 2, including the following:

- Weight
- Size
- Specific power (W/lb) as a function of specific energy (Wh/lb)
- Terminal voltage versus ampere-hours of discharge for various values of constant current
- Approximate values of charge voltage as a function of charge current and state-of-charge
- Charging restrictions, such as maximum voltage and current
- Cost
- Hazards
- Cycle life as a function of depth of discharge

4. Define development steps needed in Phase II of program to make the battery selected in Item 2 a viable selection. This would include cost estimates.

5. Provide inputs for Trade-Off Studies Report.

6. Provide inputs for incorporation in the General Electric Phase II proposal.

7. Perform a series of tests on two existing battery systems to determine the capability of the batteries to supply high current pulses in accordance with the "Pulse Testing of Batteries" two-page work description.

NOTE WITH RESPECT TO SUBCONTRACTOR'S DATA

With respect to Tasks 1 through 6 the following paragraph applies:

It is understood that all data in the Subcontractor's reports, furnished by the Subcontractor to General Electric Corporate Research and Development hereunder, may be furnished to the California Institute of Technology Jet Propulsion Laboratory and DOE and NASA with no restrictions.

With respect to Task 7 the following paragraph applies:

It is understood that only Form, Fit, and Function data will be provided for the ESB batteries to be tested under paragraph 7 of ARTICLE II. No description of the batteries will be required other than that given in the two-page Attachment to this Instruction. Accordingly, it is hereby agreed that ESB's EV 106 and experimental XPV 23 batteries to be tested hereunder shall not be subject to paragraphs (g) and (h) of Article 31. Rights in Technical Data of the General Provisions incorporated in Exhibit "A" dated 78 Oct. 16.

GENERAL ELECTRIC

Attachment to
Instruction No. 1
to Purchase Order A02000-220267
79 Mar 02

Pulse Testing of Batteries

Program Definition

Data on the performance of EV batteries at various constant current pulses is not available. In order to permit an accurate assessment of the batteries capability for supplying high current pulses a series of tests on two existing battery systems will be conducted.

Test Units

ESB Technology Company will provide for test (at no charge to GE) the following units:

Unit (A) 2 EV 106 batteries connected in series
Unit (B) 2 ESB Experimental Type XPV 23 Mod 3

These units remain the property of ESB Technology Company.

Test Sequence

1. "A" test units:
   a) Constant current discharge @ 60 A. Room temp - to limiting battery voltage (5.10) with discharge continued to 4.5 V. Recharge (to stabilized gravity level).
   b) Pulse test at 500 A as detailed below. Recharge (to stabilized gravity level).
   c) Repeat (a).
   d) Pulse test (b) @ 400 A.
   e) Repeat (a).
   f) Pulse test (b) @ 300 A.
   g) Repeat (a).
2. "B" test units:

   Repeat test sequence 1 (a through g).

Pulse Test - (A & B Test Units)

A. 1. Discharge for 12 min (10% DoD) @ 60 A.
   2. Discharge for 15 sec @ 500 A (Sequence b).
   3. Discharge for 18 min (25% DoD) @ 60 A.
   4. Discharge for 15 sec @ 500 A (Sequence b).

5. Discharge for 12 min (35% DoD) @ 60 A.
6. Discharge for 15 sec @ 500 A (Sequence b).
7. Stand open circuit for 1 min. Regen.
8. Discharge for 15 sec @ 500 A (Sequence b).
9. Stand open circuit for 1 min.
10. Discharge for 15 sec @ 500 A (Sequence b).
11. Discharge for 18 min (50% DoD) @ 60 A.
12. Discharge for 15 sec @ 500 A (Sequence b).
13. Discharge for 12 min (60% DoD) @ 60 A.
14. Discharge for 15 sec @ 500 A (Sequence b).
15. Discharge for 18 min (75% DoD) @ 60 A.
16. Discharge for 15 sec @ 500 A (Sequence b).
17. Stand open circuit for 1 min.
18. Discharge for 15 sec @ 500 A.
19. Stand open circuit for 1 min.
20. Discharge for 15 sec @ 500 A.
21. Discharge for 6 min @ 60 A.

B. 1 through 21 - Pulse values are 400 A.

C. 1 through 21 - Pulse values are 300 A.

Data Collection

Record - Amperes
- Battery Volts
- Ampere-hours discharged
- Watt-hours discharged

10 data bits before and immediately after pulse
25 data bits during pulse
Temp.

Sp.Gr. at beginning and end of test.

Battery Size and Weight

Brief description of battery construction - no proprietary data on construction, weights, etc. will be provided.

THE ASSESSMENT OF
BATTERY POWER SOURCES
THE
GE PHASE I HYBRID VEHICLE

PREPARED FOR

GENERAL ELECTRIC COMPANY

CORPORATE RESEARCH AND DEVELOPMENT

P.O. A0200-22067

ESB Project 6047

FEBRUARY 16, 1979

REPORT PREPARED BY

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ESB TECHNOLOGY COMPANY
YARDLEY, PA.

INDEX

1. INTRODUCTION

The initial detailed work statement specified the work to be performed on battery system evaluation was:

(1) Review battery characteristics [Wh/lb, (W/lb) steady' (W/lb) peak' cycle life, cost, etc.] used in hybrid powertrain screening studies.

(2) Lead-acid batteries (ISOA and advanced) - provide quantitative discussion of the following:

(a) Relationships between battery voltage and other battery characteristics (ex. size and weight, lifetime, cost, power density, etc.)

(b) Differences in design of batteries for hybrid as compared to all-electric vehicles.

(c) Battery life as a function of average depth of discharge before overnight charging; criteria for indicating depth of discharge and battery depletion in a hybrid vehicle.

(d) Relationships between depth of discharge and capability of battery to meet peak (pulsed-secs) power demand.

(e) Analytical model and supporting data for charging battery using heat engine on the road while driving.

(3) NiZn and NiFe batteries - provide quantitative discussion of the following:

(a) Projected potential of NiZn batteries especially high power capability and lifetime; effect of average depth of discharge on battery life.

(b) Projected potential of NiFe batteries especially high power capability and self-discharge tendency.

(c) Attractiveness of a hybrid battery pack using NiFe with a NiZn or Pb-acid; lifetime of the secondary storage battery (Pb-acid or NiZn) used in hybrid mode.

(d) Optimum voltage and package size for NiZn and NiFe batteries.

(e) Maintenance requiremen' of NiZn and NiFe batteries in vehicle applications.

(f) Modeling of NiZn and NiFe batteries in vehicle simulation programs.

(4) Provide estimates of costs (OEM in 1978 dollars) of lead-acid, NiZn, and NiFe batteries; discuss the effect on cost of various battery characteristic trade-off (ex. lifetime and energy density, high power capability, etc.).

Subsequent discussions at ESB on December 5, 1978 provided further clarification on the information to be provided. The battery assessment was to utilize the following guidelines:

(1) a. Battery technology as of 1981 with adequate battery units available in prototype quantities.

b. Prototype quality must be adequate to provide 100,000 systems/year in 1985.

(2) Candidate battery systems are:

Lead Acid - ISOA

Lead Acid - Advanced

NiZn

Li-S

NaS

(3) Performance of vehicle must be comparable to 1/c unit, i.e. 0 to 60 mph in 15 sec.

(4) Peak power for acceleration (passing) may be up to 25 sec. in duration.

(5) Concept is to maximize use of battery and minimize use of internal combustion engine.

(6) Vehicle should reach its daily end of duty cycle with the least possible battery reserve and least use of petroleum based fuel.

2. STATUS OF COMPETITIVE BATTERY FOR HYBRID VEHICLES

2.1 Lithium Metal Sulfide Cell Systems

Appendix A contains the technical analysis and performance data available on this system. Some additional facts are worth noting:-

- During the last few years the power characteristics of the system have been improved but at a sacrifice in cycle life, or the cycle life has been increased at a sacrifice in power output.
- The cost data given in Table 5 does not include cost of the oven to maintain battery/cell at desired temperature.
- Cost is based on having capitalization to do mechanized assembly in dry boxes or in controlled atmosphere areas.
- There do not appear to be significant freeze-thaw problems in the Li-FeS system.
- System must use cylindrical vacuum type thermos chamber to contain prismatic cell to meet heat loss goal of 150 W on 40 Kwhr battery.
- Overcharging results in the development of Fe[illegible] which corrodes lower cost current collectors. ANL reports they have developed a cell bi-pass system (at a cost of $5.00/Kwhr that can handle up to 5% of the current in a series string of cells on overcharge.
- Major Obstacles to be overcome are:
    - Economics - oven costs and mechanical assembly in glove box.

- Power per unit Wt. simultaneously with acceptable cycle life.
- Offers possibility in 1990's if above obstacles can be overcome.

2.2 Sodium Sulfur System

Appendix B contains technical data and analysis of this system.

- Chloride in England will provide first real test of the system in 19,9.
- There still remains the problem of β alumina tube and seal reliability (and cost);
- Progress has been made in overcoming the corrosion problems by placing the sodium of the outside of the β alumina tube and thus permit use of carbon steel containers.
- Freeze-thaw problem remains and warm-up after freeze becomes major problem as cells get larger in size. Thaw problem appears to be related to differential expansion of sulfur and β alumina causing tube cracking at glass seal interface.
- Calcium and potassium impurities in Na decreas_ life of β alumina in cycling tests.
- Overcharging is not permitted. While NaS systems do not develop gas pressures, insoluble compounds are formed in the sulfur mix which increases the cell resistance and cause imbalance in the series - parallel assembly
- Major obstacles to be overcome
  - Economics (tube costs are @2.50/sq. cm with goal of 1-2 ¢/sq cm of surface)
  - Reliability and cost of seals
  - Reliability and cycle life of β alumina tube

- Freeze-thaw problem
- Safety under EV mechanical environment.

2.3 Conclusions re Molten Salt Systems

1. Life cycling data is sketchy
   - British Railroad 6 cell 250 Whr unit gave 1000 cycles.
     (a) R. J. Banes & D. A. Teagle - Experimental Study of Six Interconnected Na-S cells, J. Power Sources 3, 45 (1978).
2. Cell and component evaluations are still being actively pursued but few batteries have ever been assembled and/or tested.
3. First Molten Salt application will be '83 BEST facility test of 2.5 M Whr. Na-S battery. Chloride will be testing a Na/S battery in a van in '79.
4. Reliability in β alumina tubes is a continuing problem.
5. System does not appear suitable for consumer EV usage since safety is still of major concern.
6. Cell balancing by overcharge is not feasible due to the inability to overcharge without permanent damage to cell.
7. Thermal shock problems remain unresolved as to how to survive start up after freezing in large Na-S cells.
8. Seal reliability continues to require study and further improvement.
9. Basic material costs do not look too excessive with Na @ 41¢/lb but substantial capital investment will be required to minimize costs.
10. β alumina cost reduction will only be achieved as a consequence of the development of a load leveling or other large market demand.
11. Power density of molten salt cells is not attractive. Present prediction is that power/Wt and cycle life cannot be mutually achieved; NaS has better capability than Li(Al)/E 5.

11. • Na/S requires substantial paralleling of cells.

    • Li/FeS can multiple plate cells thus reducing need for paralleling.

12. Molten Salt

    • Systems will not be developed to permit "battery" evaluation to be completed by 1981 on a single design concept.

2.4 Nickel Iron Battery System

Appendix C contains the technical analysis and data on this system. As indicated, non proprietary data is limited but additional comments are warrented.

NiFe

- Best nickel iron cells in Europe are Daug (German) cells but little data are available although tests have been underway for some time.
- Swedish Su iron electrode costs are said to be 1/3 of Ni electrode cost but since process is proprietary these cannot be justified.
- Swedish Su electrode is reported to have highest efficiency due to .8mm thickness. Westinghouse iron electrode is reported only 60/70% as efficient as SU.
- Problems of iron contamination on nickel electrode are beginning to be reported.
- Thermal control is required since NiFe system is inherently inefficient at high and low temperatures.
- Water addition and frequent servicing is needed.
- Electrolyte circulation has been proposed as a means of overcoming thermal problems but this introduces even more difficult problems.
- O.C. capacity loss is 2.2%/day for the SU electrode.
- Low cell voltage necessitates additional cells in series. 1.12v for NiFe vs 1.50v for NiZn vs 1.95v for Pb.

2.5 Nickel Zinc Battery Systems

Appendix D contains the technical analysis and data on this system. Major emphasis has been given to conventional nickel zinc systems since data on the ESB Vibrocell® system is still limited. Additional comments on the nickel zinc system follow.

- Cycle life is still the major problem. It is aggravated by very high temperature rise during cycling of present cells.
- System tests with large size cells in excess of 100v show wide performance variations.
- Zinc poisoning of the nickel electrode is emerging as a problem.
- Separators for EV-Hi power applications are still sought. Inorganic separators that reportedly have long life are too resistant to permit high rate discharge.
- Cost of Ni and cost of cell assemblies remain as major obstacles.

The ESB Vibrocell® capacity degradation with cycling appears to be less than with conventional cells.

- Vibrocell® is probably more sensitive to power demands due to need for spacing between electrodes.
- Polarization appears to be minimal in the Vibrocell® negative.

2.6 Lead Acid Batteries

The lead acid battery has been the most widely used power source for propelling electric vehicles in use today. The golf cart, the forklift trucks, and mine locomotive are typical examples of motive power use. In general, these applications stress long life, reasonable power and energy density and cost. Weight has never been of major concern.

The other major usage of lead acid batteries is the SLI market where major emphasis has been directed toward maximizing cold cranking (amps) performance.

The Department of Energy's contracts with ESB, Globe and C&D (Eltra) managed by Argonne National Labs are directed at two levels of improvement.

1. Improved State-of-the-Art.
2. Advanced Batteries.

These goals are given in Table 1. Each of the three subcontractors has expressed confidence in being able to simultaneously achieve all of the ISOA goals.

Figure 1 shows a typical Ragone plot (Watts/Kg vs Watt hr/Kg) for the present Golf Car (EV106) battery to which have been added a line for "Improved Golf Car" and the ISOA and Advanced Battery goals. Data from ESB experimental cells and batteries tested in July 1978 have been added to indicate performance that has been achieved. Similar results have been indicated by other DOE contractors. Life test data is still being accumulated but the risk in this area does not appear to be too great. Cost goals (based on '76 estimates) should be achievable; actual prices will rise since '76 estimates were based on 25¢/lb lead with Feb '79 lead at the 44¢/lb and rising!

Since this development effort is based on "Improving the State-of-the-Art", manufacturing facilities are available to supply initial requirements for the EV market and scale up can be accomplished on a schedule consistent with the scale up required by the vehicle manufacturers.

Table 1

ARGONNE NATIONAL LABORATORY

CONTRACT 31-109-38-4207

PRELIMINARY BATTERY DEVELOPMENTAL GOALS

		ISOA	ADVANCED
1.	BATTERY CAPACITY (KW-HR)[A] (100% RATED)	20 - 30	30- 40
2.	BATTERY DIMENSION (CM H x CM W x CM L)	29.5x40.6x264	29.5x40.6x264
3.	SPECIFIC ENERGY[A] (W-HR/KG)	40	60
4.	SPECIFIC POWER (W/KG) PEAK BATTERY - 15 SEC. AVG.	100	150
5.	DUTY CYCLE		
	CHARGE (HR)	4 - 8	4 - 8
	DISCHARGE (HR)	2 - 4	2 - 4
6.	LIFETIME		
	DEEP DISCHARGES[B]	800	1000
7.	PRICE/ENERGY[C] ($/KW-HR)	50	40
8.	ENERGY EFFICIENCY (%)[D]	60	60
9.	TYPICAL INSTALLATION VOLTAGE[E]	96-120V	96-120V

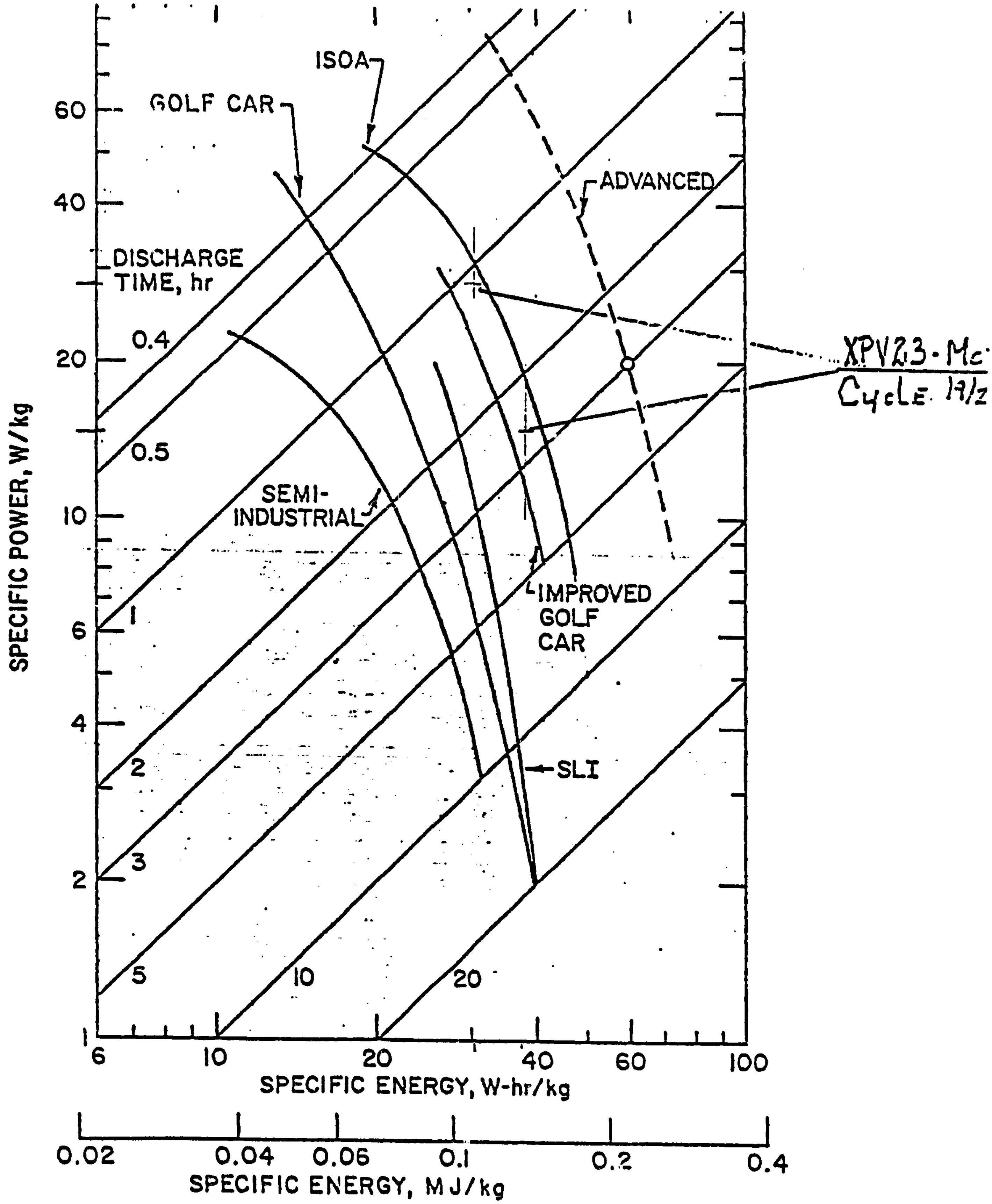
[A] C/3 RATE DISCHARGE; 8-HR CHARGE. THE 3 HR RATE IS DEFINED AS A 3 HR CAPACITY OF A BATTERY TO 1.75V/CELL AT 26.7°C (80°F)

[B] 80% DEPTH OF DISCHARGE FROM RATED CAPACITY.

[C] PRICE F. O. B. TO AUTO MANUFACTURER WITH PRODUCTION ~10,000/YR.

[D] AT BATTERY TERMINALS INCLUDING AUXILIARY EQUIPMENT, EXCLUDING CHARGER.

[E] FOR COMPACT PASSENGER CAR.



Performance of Various Lead Acid Battery Systems

Figure 1

The goals of the Advanced Battery program are more severe and will require significant breakthrough to simultaneously achieve all of them! Achievement of several goals with a relaxation of others appears to be a more moderate level of achievement in the next two to three years.

Based on the best available data, the performance of the lead acid battery available in 1981 to meet the Phase I Hybrid goals will be that described by the DOE ISOA program.

Table 2

Energy Storage and Power Parameters(Projected to 1981)

Battery Type	No Load-Leveling			Load Leveled		Secondary Storage
	wH/lb	$(w/lb)_{sp}$	$(w/lb)_{pp}$	wh/lb	$(w/lb)_{sp}$	$(w/lb)_{pp}$
1. Lead-acid - EV 1978	13	20	50	16	20	100
2. Lead-acid - 1981 (ISOA)	18.2	45	70	24	35	150
3. Ni-Zn	30	55	85	40	55	200
4. Ni-Fe	25	25	60	32	25	75
5. Li-FeS (Mark IA)	30	20	30	35	20	35
Flywheel (composite)	7	-	-	-	-	-

Cost and Lifetime Parameters

Battery Type	\$/Kwh	\$/lb	Cycle Life	Years Life
1. Lead-acid - EV 1978	50	.85	500	2
2. Lead-acid - 1981 (ISOA)	50	.65	800	4
3. Ni-Zn	200	2.6	200	3
4. Ni-Fe	200	1.6	1000	6
5. Li-FeS	200	5.3	800	5
Flywheel (composite)	400	4.0	-	10

3. CONCLUSIONS AND RECOMMENDATIONS

Lead acid batteries are the only energy storage sources that are sufficiently developed and available to meet the requirements and schedules for pure electric and hybrid electric vehicles. Advanced battery systems now under development still have sufficient problems to make them doubtful candidates for mass production or use for the next decade.

Table 2 tabulates the projected 1981 data on the systems examined in this effort. Data on Flywheel is included based on information supplied by GE.

Appendix A

Li(Al)/FeS_x Battery Systems

Under DOE sponsorship and the direction of ANL Eagle-Picher, Gould Inc., and others are in the process of commercialization of technology developed by ANL and these industrial organizations for the Li/LiCl-KCl/FeS_x molten salt system.

The enclosed information has been gleaned from ANL, IECEC, and other publications during 1978 and represents the better cell designs fabricated and tested. Ragone plot data are very difficult to obtain from these publications because in most cases the cells tested are not discharged at more than two or three rates and Whr/kg data are not always calculated and published with its associated W/kg values but rather a peak W/kg value is given for each of a variety of cell designs.

Table 1 summarizes early cells manufactured in 1976 and tested in 1977 and represents prismatic designs made in the discharged state. Table 2 is similar data for two plateau Li/FeS_2 cells made in the discharge state about the same time at ANL.

Table 3 gives data for selected Eagle-Picher cells showing peak power and specific energy in Whr/kg for their two plateau FeS_2 cells. Table 4 gives Ragone plot data read from curves in the paper by Dr. Duane Barney at the Second Annual Battery & Electrochemical Technology Conference, June 5-7, 1978, entitled "Development Status of Li/Metal Sulfide Batteries." See enclosures 1 and 2 for applicable curves. Gould cells have lower energy densities to date.

The corresponding Ragone plot is given as Figure 1.

Table 5 is a recent ANL optimization study comparing performance and costs as a function of the number of positive plates in their proposed multiplate cell. These data were given by H. Shimotake at the May 9-10, 1978 Annual DOE Review at ANL. See enclosure 3.

Figure 2 summarizes this and earlier data and compares performance to ANL goals for cells and batteries. While projections have been made, no experimental data on EV batteries have been published; however, tests by Eagle-Picher on the Mark IA 40 kWhr battery should now be in progress. Enclosure 4 summarizes the present state of the art in cells vs. battery goals as a function of calendar year of development.

Major concerns are power density in Li/FeS cells which give relatively good cycle life, and cycle life in Li/FeS_2 cells which give higher and relatively good power and energy density. Projected costs have also risen and are likely to increase even more.

Table 1

Uncharged Prismatic LiAl/FeS Cells*

Cell S/N	Capacity Ahr	Specific Energy Whr/kg	Specific Energy Whr/l	Specific Power W/kg	Cycle Life	Efficiency % Ahr	Efficiency % Whr
R-5	42	63	[illegible]	25	> 600	96	85
R-6	45	67	190	29	> 550	96	86
R-7	76	100	300	45	179	95	85
R-9	77	100	300	45	7	95	85

* Al/Fe-Li_2S; R-6 contains Cu ($10\%_w$); R-7, 9 contains Cu ($20\%_w$).

Table 2

Uncharged Prismatic LiAl/FeS Cells**

R-2	65	110	320	110	143	99	80
R-3	72	105	310	110	24	92	60
R-8	72	105	310	110	> 360	99	85

** Al/Fe-Li_2S-Co.

F. Hirschfeld, Mechanical Engineering, June 19[illegible], p [illegible].

TABLE 3

Eagle Picher Two Plateau Li-Al/FeS$_2$ Cells

Cell S/N	Capacity Ahr	Specific Energy, Whr/kg 40 mA/cm^2	Specific Energy, Whr/kg 60 mA/cm^2	Peak Power W	Internal Cell Resistance mΩ
I8L-034	220	120	99	106	6.6
I8H-040	117	98	64	136	5.3
I73	222	91	79	126	6.9
I6A1	155	83	67	94	9.0

TABLE 4

Effect of Discharge Rate on Specific Energy
430°C (400-600 Hrs Life)

Cell S/N	Discharge Rate hrs	Discharge Current A	Specific Energy Whr/kg	Specific Power W/kg	Peak Power 100%C W	Peak Power 50%C W
034	9	24	112	22		
	6	37	103	36		
	3	73	82	52		
					106	62
173	9	25	[illegible]	[illegible]		
	6	37	85	28		
	3	74	[illegible]	[illegible]		
					121	70

References (1) E. C. Gay et al, Review of Industrial Participation in the ANL Li/FeS$_x$ Battery Development Program, 13th IECEC, Paper 789202, p. 590, August 20, 1978.

Table 5

Design a Cost Optimization Multiplate LiAl FeS Cell

(100 Ah Case)

Number of Pos. Plates	Specific Energy Wh/kg	Specific Power W/kg	Cost, $/kWhr Act. Materials	Other Parts	Total
2	109	[illegible]	9	20	29
3	116	190	8	27	35
4	115	190	7	36	43

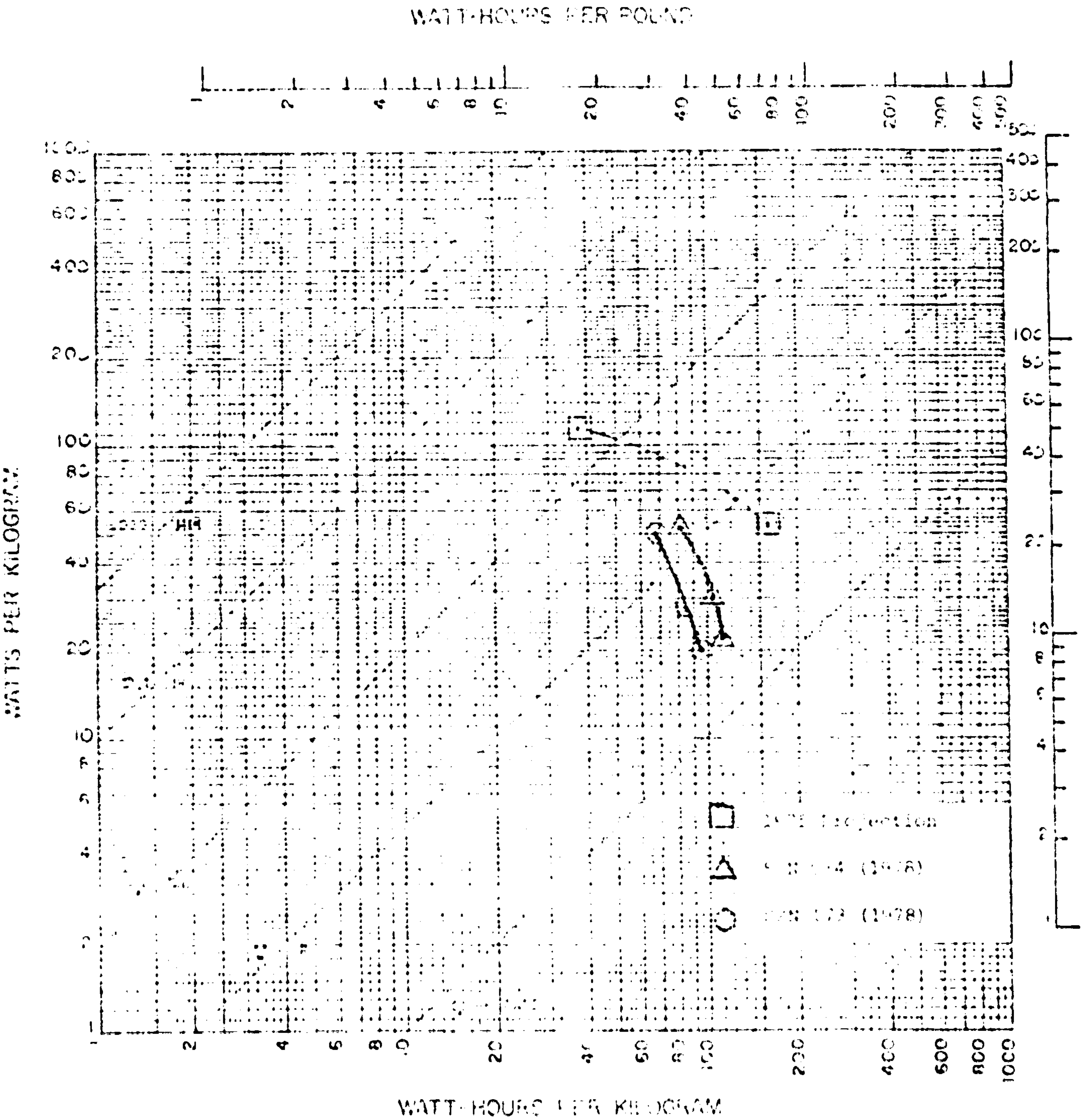


Figure 1. Eagle-Picher FeS$_2$ Cells - S/N 0.4 and 173

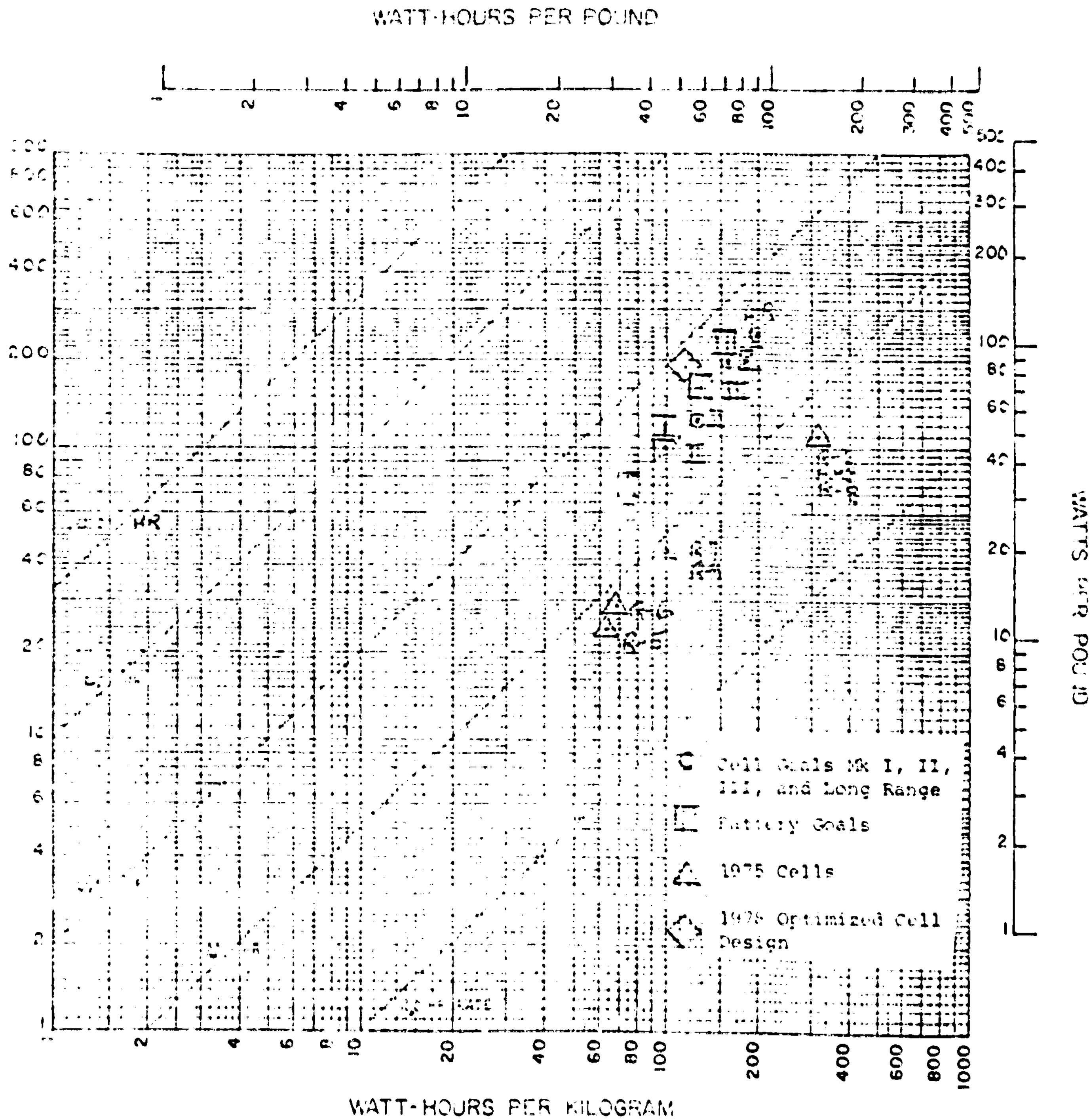
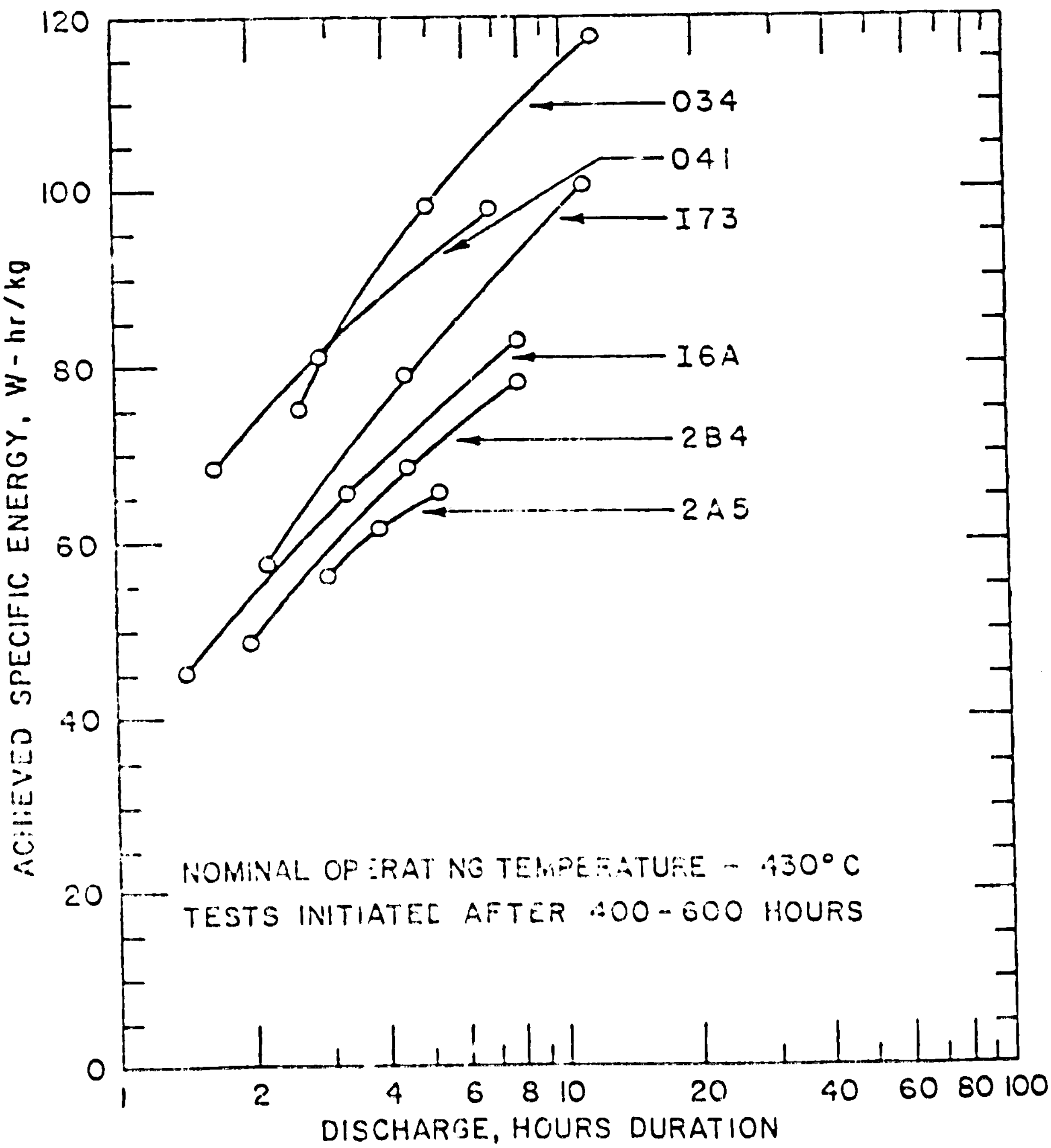


Figure 2. Li(Al)/FeS_x Cell Performance vs. Goals

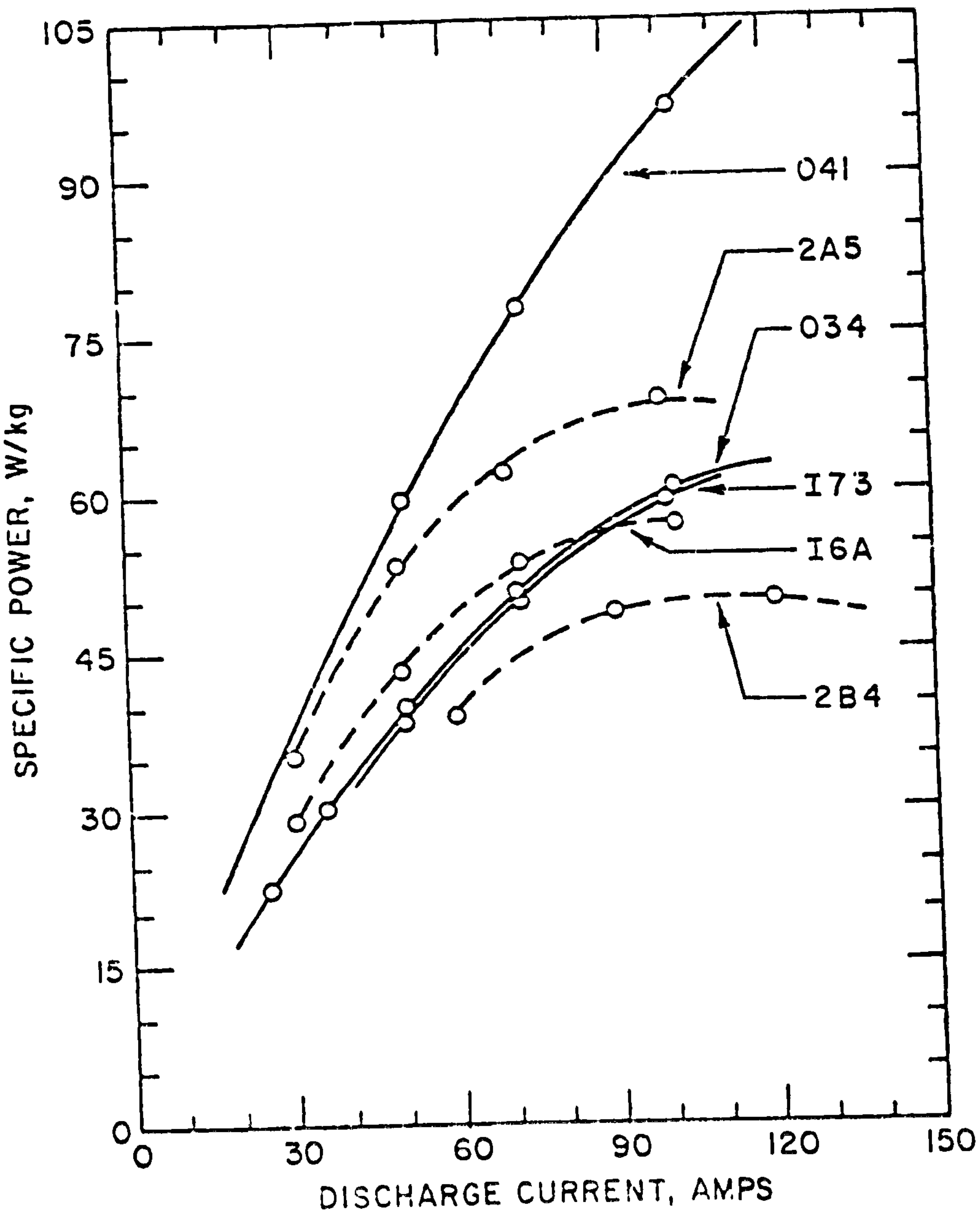
Specific Energy of Eagle-Picher FeS_2 Cells vs. Discharge Rate in Hours.

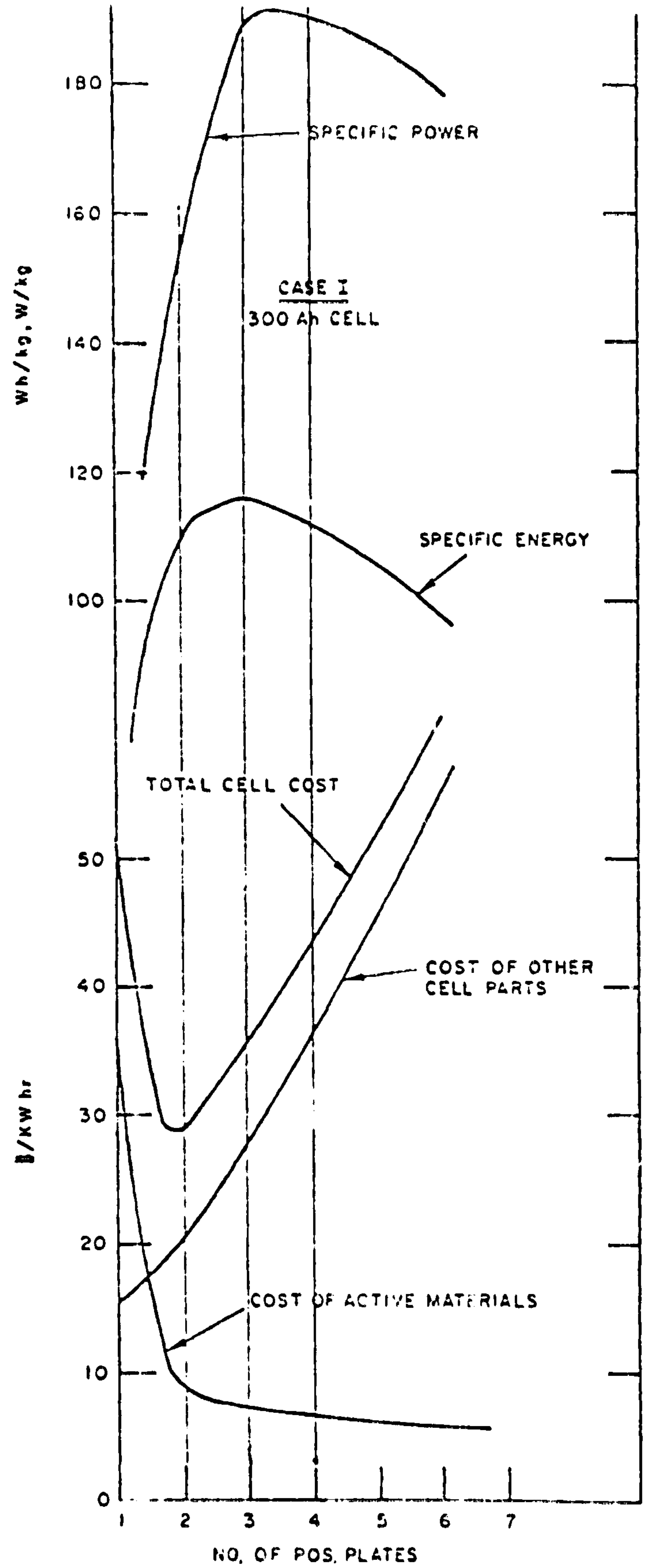
SPECIFIC ENERGY OF EAGLE PICHER FeS_2 CELLS



SPECIFIC POWER OF EAGLE PICHER FeS_2 CELLS

CELL	WATTS PEAK POWER CHARGED	WATTS PEAK POWER 50% CHARGED	RESISTANCE MILLI-OHMS
041	136	79	5.3
034	108	60	6.6
I73	125	70	6.9
I6A	95	57	9.4
2B4	97	65	7.5
2A5	86	69	8.5

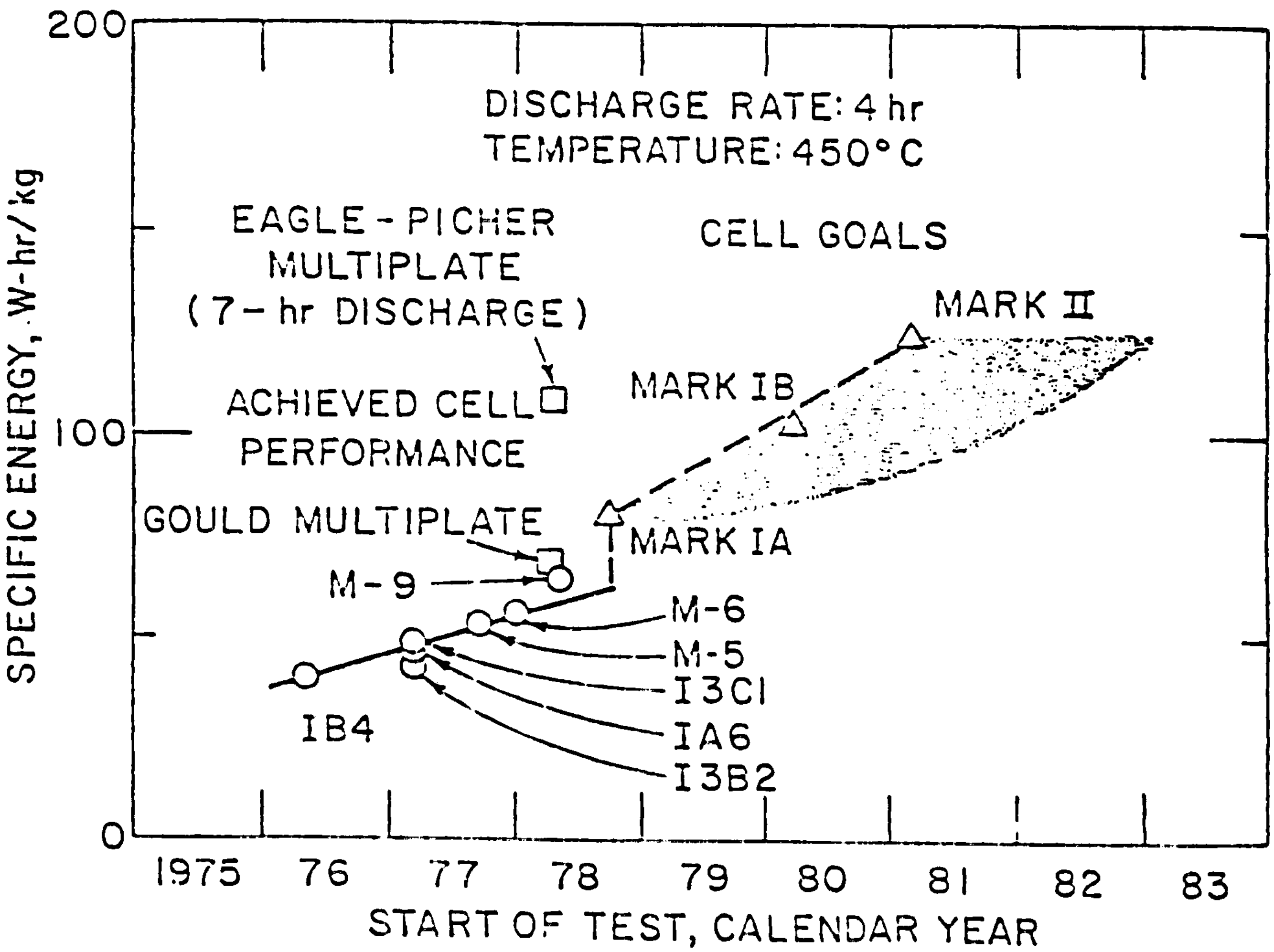




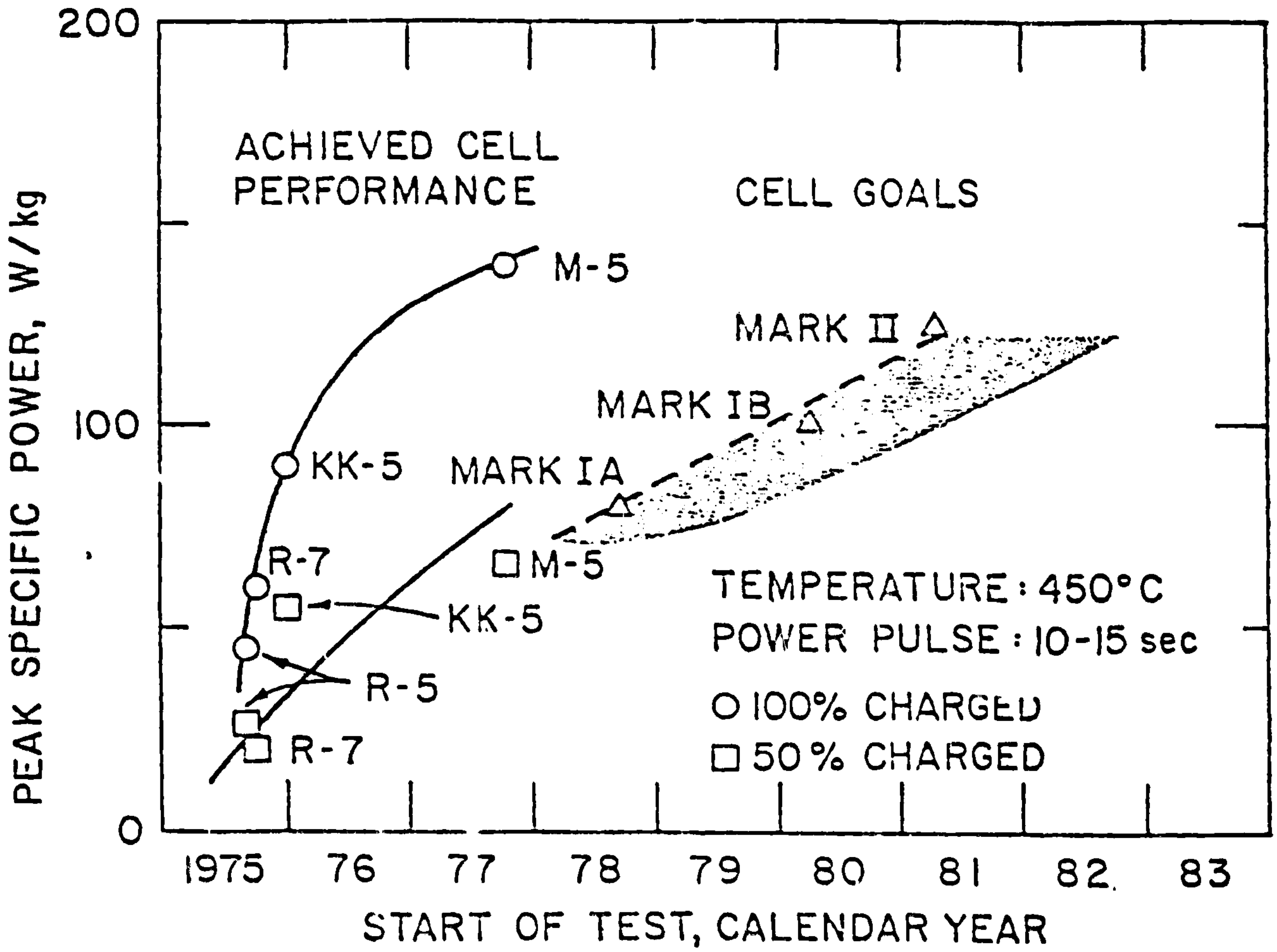
DESIGN AND COST OPTIMIZATION OF A MULTIPLATE LiAl/FeS CELL

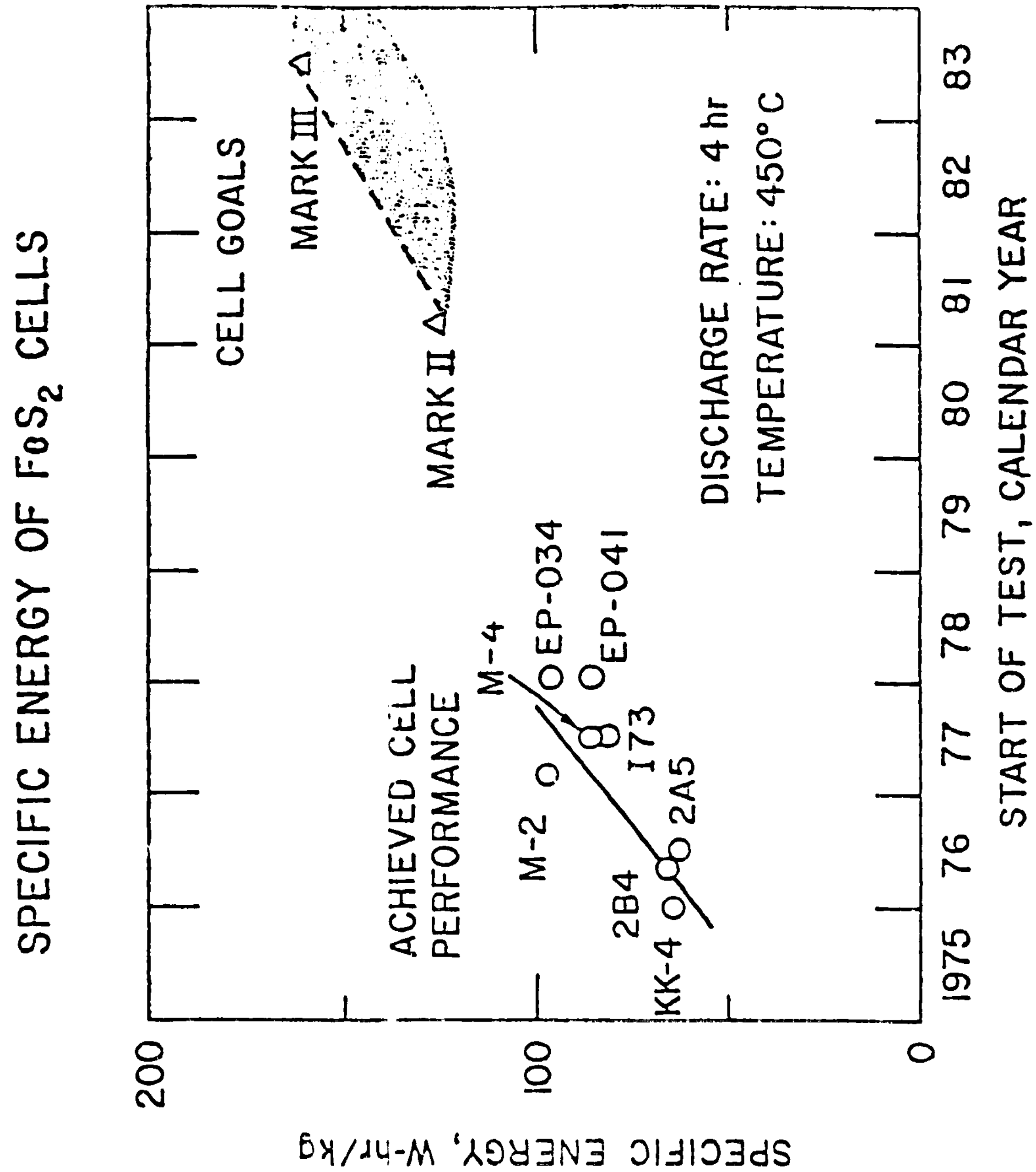
Enclosure 3. Specific Energy, Power & Cost per Cell vs. Number of Positive Plates in Multiplate L./FeS Cells.

SPECIFIC ENERGY OF FeS CELLS

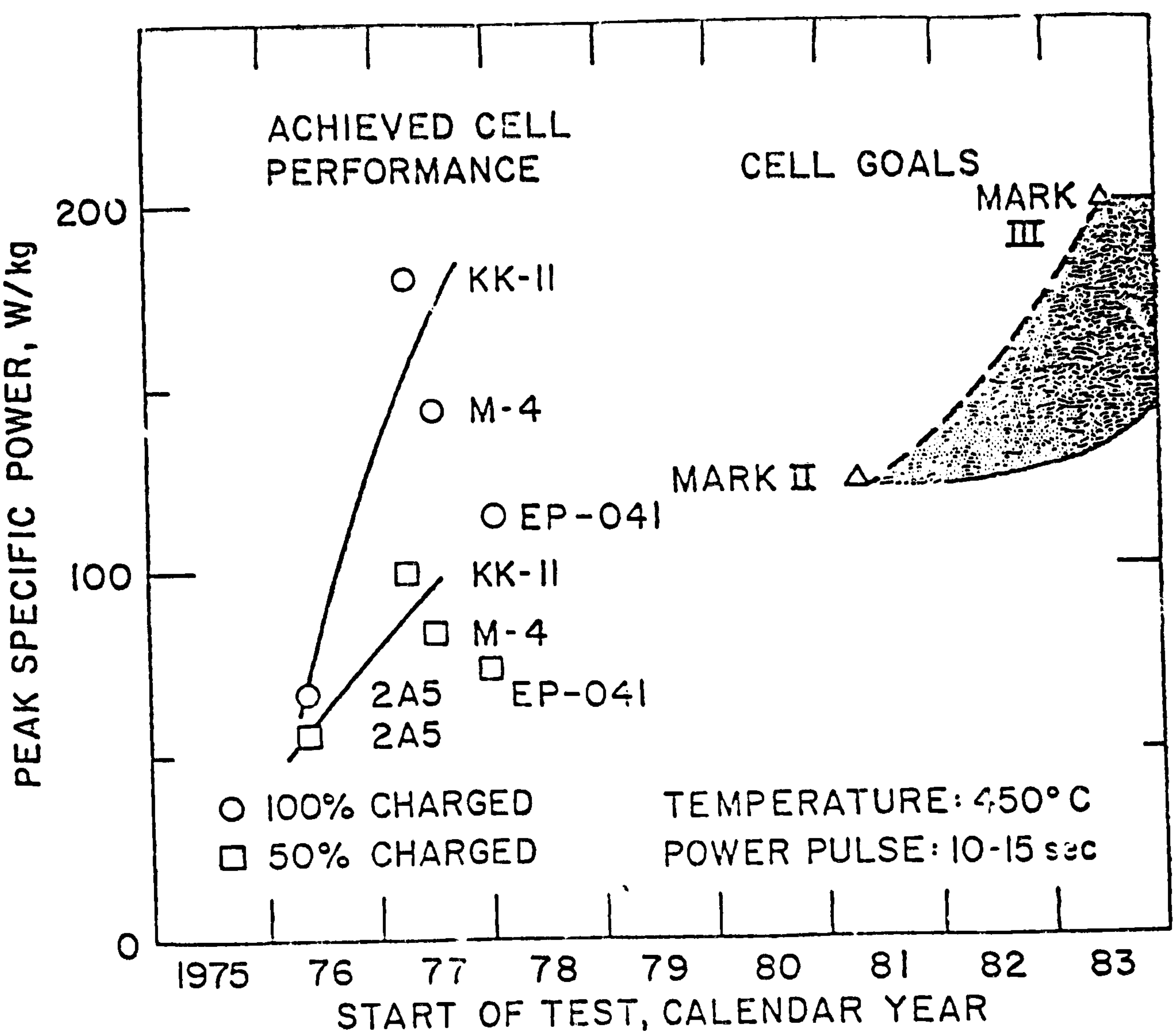


PEAK SPECIFIC POWER OF FeS CELLS

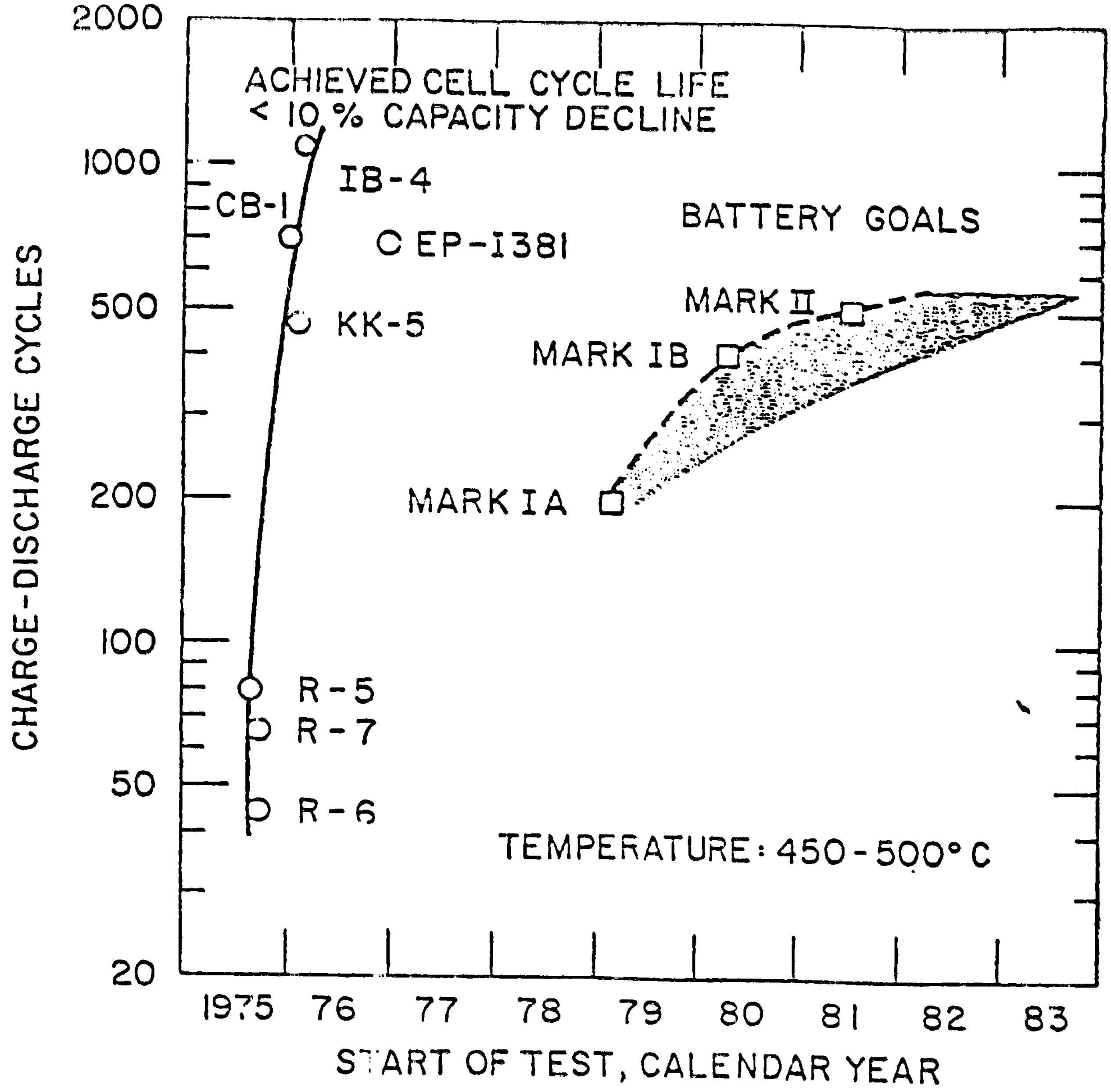



SPECIFIC ENERGY OF FeS$_2$ CELLS
CELL GOALS
MARK III
MARK II
ACHIEVED CELL PERFORMANCE
M-4
EP-034
EP-041
I73
2A5
M-2
2B4
KK-4
DISCHARGE RATE: 4 hr
TEMPERATURE: 450° C
1975
76
77
78
79
80
81
82
83
START OF TEST, CALENDAR YEAR
200
100
0
SPECIFIC ENERGY, W-hr/kg

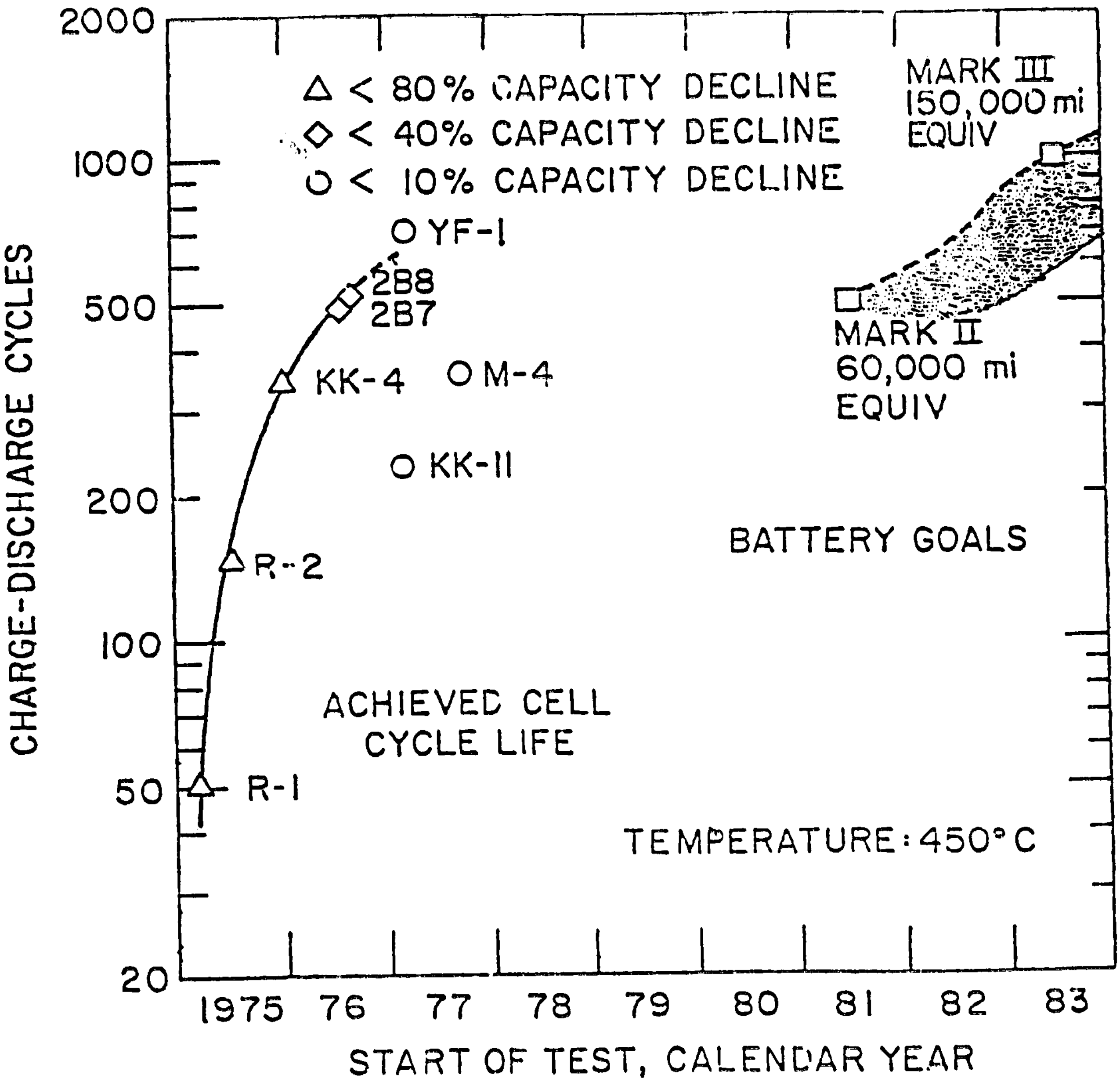
PEAK SPECIFIC POWER OF FeS_2 CELLS



CYCLE LIFE OF FeS CELLS



CYCLE LIFE OF FeS_2 CELLS



PROGRAM GOALS FOR THE LITHIUM/IRON SULFIDE ELECTRIC VEHICLE BATTERY

	Mark I	Mark II	Mark III	Long-Range
Specific Energy, W-hr/kg				
Cell (average)[a]	100	125	160	200
Battery	75	100	130	155
Energy Density, W-hr/liter				
Cell (average)	320	400	525	650
Battery	100	200	300	375
Peak Power, W/kg[b]				
Cell (average)[a]	100	125	200	250
Battery	75	100	160	200
Jacket Heat Loss, W	300	150	125	75-125
Lifetime				
Deep Discharges	400	500	1,000	1,000
Equivalent Miles	40,000	60,000	150,000	200,000

[a] Individual cells for Mark I will have 10% excess capacity and power above that shown to allow for cell failures and mismatching; individual cells for Mark II will have 4% excess capacity and power.

[b] Peak power sustainable for 15 sec at 0 to 50% of battery discharge; at 80% discharge, peak power is to be 70% of value shown.

Appendix B

Ford Na B"/S Battery System

Table I gives the best estimates which can be derived for the Ford A-130-12 EV single tube cell now being tested for EV applications on their DOE contract.

Table II gives the estimated energy, power and energy-power densities Ford projects for the Ford Fiesta battery composed of 48 cells in series and 14 sub-cells bundled in parallel in each cell. This battery has been described as the 40 kWhr unit type 48(A130-12)14.

Figures 1 and 2 are Ragone plots giving the difference between cell and battery performance. Ford's slides by N. A. Fulick gave the following energy densities as realistic targets for EV's.

Assembly Condition	Volume Density Whr/l	Weight Density Whr/kg
Theoretical	850	760
Single sub-cell	358	175
Battery with thermal management	222	155
Installed in EV	115	120

The last energy density penalty for installation is common to all systems and includes weight and volume needed for mounting the battery against shock and vibration and ready interchange.

Note in Table II the energy factor 1.41 as the excess energy to assure the required energy is available to give the required range of 100 miles at the test weight of 2470 lbs:

	Weight-lbs
Base Vehicle	1254
Payload	350
Motor and Controller	206
Battery	565
Mounting Structure	96
Test Weight:	2470

Ford's estimate requires an energy of 28.[illegible] kWhr per 100 miles. The 40 kWhr battery described would deliver 40/1.41 = 28.4 kWhr.

The major open issues are listed by Ford as long term stability of performance, reproducibility of cells, life of cells on EV regime in automobile, optimization of cell arrangement, insulation and thermal management.

We have to add that at the time this data was issued at the November 1978 Program Review, Ford scientists stated privately that cool-down to the frozen state and warm-up back to 350°C cannot be accomplished without cracking the beta tubes.

Ford believes, and we have confirmed, that it is the differential expansion of the beta and the sulfur electrode which is responsible. We have taken 20 Whr Na-S cells through this thermal freeze thaw shock successfully but not large tube Na-S cells. It will be a major problem area for Ford.

TABLE I

Basic EV Na/S Cell Characteristics

(Estimates)

Discharge Time Hr	Discharge Current A	Capacity Ahr	Voltage Mean Volts	Energy Whr	Power W	Energy Density Whr/kg	Energy Density Whr/ℓ	Power W/kg	Power W/ℓ
5	6	30	2.01	60	12	181	370	36	74
4	7.5	30	1.97	59	15	178	364	45	91
3	10	30	1.92	58	19	175	358	58	119
2	15	30	1.85	56	28	169	346	85	173
1	30	30	1.75	52	52	157	321	157	321
15 sec					147				

Cell Volume: 0.162 ℓ

Cell Weight: 0.331 kg

Recharge Time: 8 hrs

Source: Ford Na/S Program Review, Newport Beach, Calif., 1 November 1978.

TABLE II

Ford Fiesta 40 kWhr Na/S Battery

Type 48 (A-130-12) 14

Discharge Time	Discharge Current	Capacity to 1.6 V	Voltage Mean	Energy Output	Power	Energy Density		Power Density	
Hrs	Amps	Ahr	Volts	kWhr	kW	Whr/kg	Whr/ℓ	W/kg	W/ℓ
5	84	420	96.5	40.3	8	157	237	31	47
4	105	420	94.6	39.6	10	155	233	39	59
3	140	420	92.2	38.9	13	152	229	51	76
2	210	420	88.8	37.6	19	147	221	74	112
1	420	420	84.0	34.9	35	136	205	137	206
15 sec					99			387	582

Battery Weight: 256 kg (Including heat retaining insulation and close packed cells with all equipment for thermal management).

Battery Volume: 170 ℓ

Recharge Time: 8 hrs

$E_{Battery} = 1.41\ E_{required} = F_1 \cdot F_2 \cdot F_3 \cdot F_4 \cdot E_{required}$

F_1 = depth of discharge factor = 1.25

F_2 = single cell failure factor = $1 + \frac{1}{N_p}$ where N_p =

= number of cells in parallel = 14

F_3 = non-uniform operation factor = $1 + \frac{0.152}{U \quad N_p}$

F_4 = cell aging factor = 1.1

$\therefore$ $E_{required}$ is 28 kWhr for above battery.

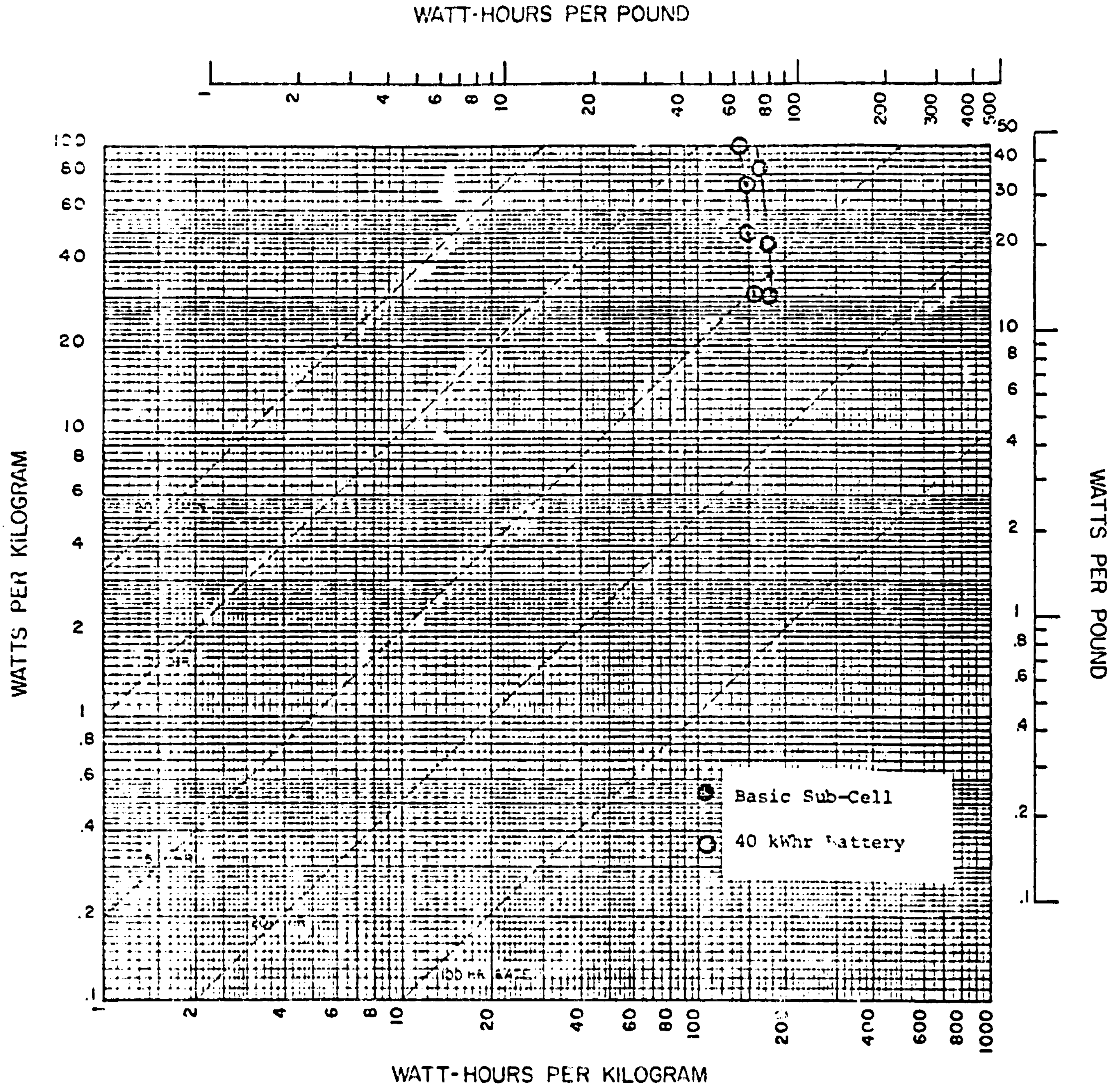


Figure 1. Weight Energy Density of Ford Fiesta Na/S Battery

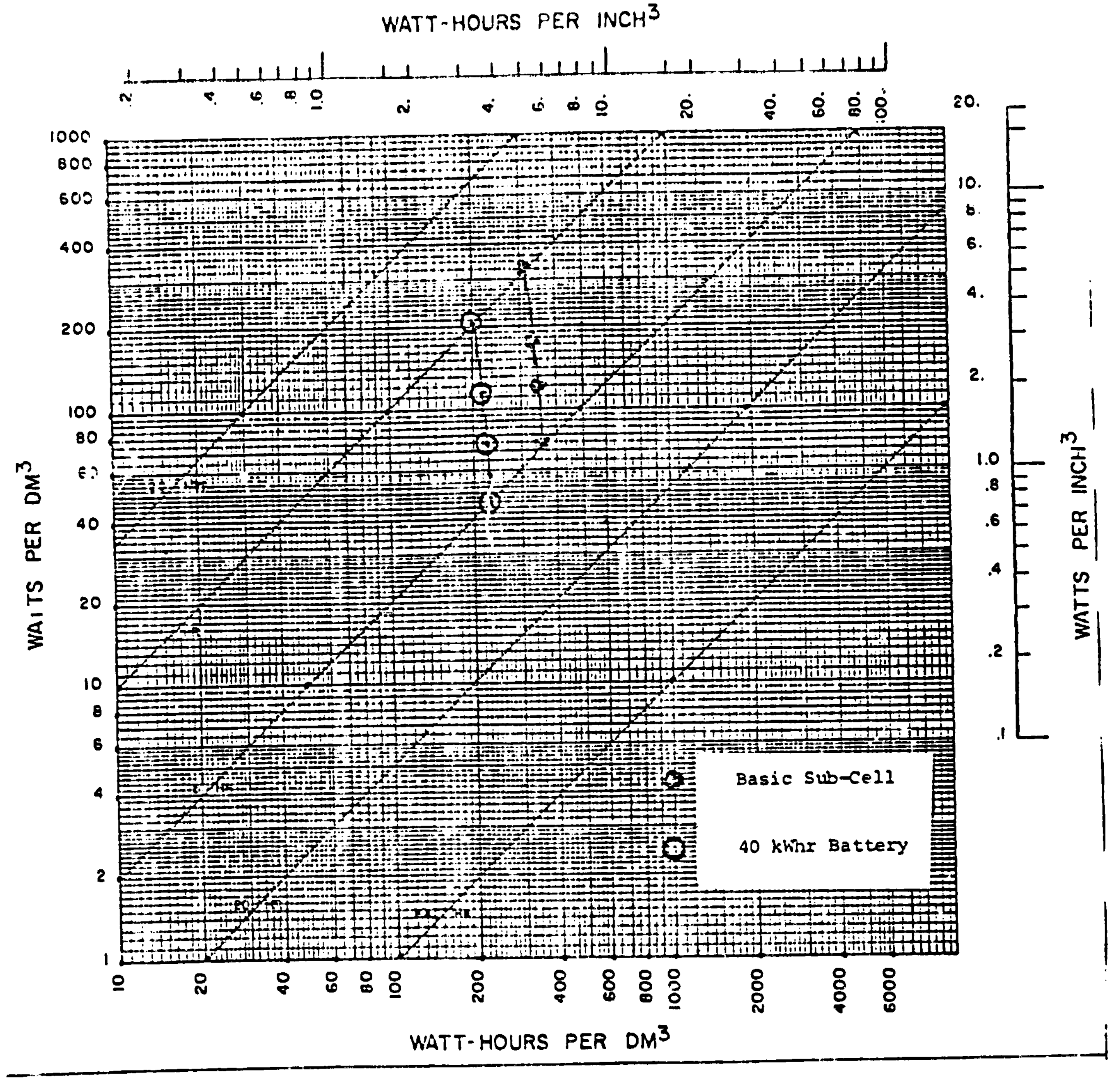


Figure 2. Volume Energy Density of Ford Fiesta Na/S Battery

Appendix C

Nickel Iron Battery System

NICKEL/IRON EV BATTERIES

1. Background

The U. S. Department of Energy has let two contracts for the development of nickel/iron electric vehicle batteries: one to Westinghouse Electric Corporation and one to Eagle-Picher Industries, Inc. Westinghouse has demonstrated laboratory cell performance which nearly matches the long-term program goals and is developing an alternative nickel electrode production scheme which uses the lowest-cost forms of nickel. Eagle-Picher has begun assembly and testing of full-scale improved nickel/iron cells. The iron electrode technology being developed in conjunction with the Swedish National Development Co. (Åkersberga, Sweden) may offer the potential for the best energy efficiency ever achieved in a nickel/iron battery.

2. Goals and Present Specifications

	Goals	Present
Price ($/kWhr)	60	120
Specific Power (W/kg)	100 @ 17% V drop	100 @ 24% V drop
Energy Efficiency (% at C/3 Disch. and 6-hr charge)	60	55
Life (Cycles at 80% rated capacity)	2000	1500
Specific Energy (Whr/kg)	60	44

3. Nickel/Iron Battery Advantages and Disadvantages

Advantages:

- Cell reversal not damaging
- Long life

Disadvantages:

- History of high cost
- Open circuit cell voltage only 1.2 V
- Self-discharge is somewhat high and worsens with age (Westinghouse projects their future battery to lose 1.67% per day so that a two-week open circuit stand would result in a loss of approximately one quarter of the original capacity.)

- Poor low temperature performance
  (A Ni/Fe system with an electrolyte temperature of 0°C yields only 43% of its 25°C capacity [to a 1.0V per cell cut-off]. This may require heaters and extra insulation compared to other systems.)
- Maintenance (watering) requirements probably higher than Pb-acid systems.
- Thermal management (heat build-up) problems may be severe.

4. General Comments

A hybrid vehicle pack using Ni/Fe and lead-acid would hold no significant advantage. The Ni/Fe system energy and power densities, although higher than Pb/acid, are not that much better to justify the complexities and additional expense of going hybrid. If the cycle life of Ni/Zn is improved, the Ni/Zn - Pb/acid hybrid would be more attractive.

The modeling of Ni/Fe batteries in vehicle simulation programs is not possible without specific performance and/or specifications from the EV battery contractors. Both Eagle Picher and Westinghouse have been guarding the release of information pertaining to the Ni/Fe vehicle battery program.

In addition to the program in the United States, DAUG (Deutsche Automobil-gesellschaft MBH) in Esslingen, Germany has had a serious Ni/Fe vehicle battery program for years and is testing batteries in van-type vehicles.

The ability to supply prototype quantities of Ni/Fe batteries in '81 and large quantities in '85 would probably be shared by all three companies - Westinghouse, Eagle-Picher and DAUG. The cost estimates, however, are always to be questioned in an untried vehicle system. I have heard unofficial comments in Sweden, for instance, that the cost estimates for the production of the SU iron electrode were unrealistically low. The process is, however, proprietary and therefore not open to objective analysis.

Ni/Fe Power and Energy Densities at Different Rates

Rate	Westinghouse Claims:	G. E. Curve
C	54.8 W/kg (54.8 Wh/kg)	46.9 W/kg (46.9 Wh/kg)
C/3	20.6 W/kg (61.8 Wh/kg)	22 W/kg (66 Wh/kg)
C/5	13.2 W/kg (66 Wh/kg)	14 W/kg (70 Wh/kg)

Appendix D

Nickel Zinc Battery System

NICKEL/ZINC EV BATTERIES

1. Background

Under the provisions of the McCormack Act, the U. S. Department of Energy has contracted with three companies to develop Nickel-Zinc EV batteries. These companies (Yardney Electric, Energy Research and Gould) along with Eagle Picher had completed Phase I study contracts before being granted the development contracts. In addition, General Motors is carrying out an in-house Ni-Zn development without benefit of government funding. All of these efforts are concerned with Nickel-Zinc batteries of "conventional" design; i.e., cells with closely packed electrode elements, incorporating barrier type separators. In addition to this work, ESB and its Swedish subsidiary, AB Tudor, are working on the development of vibrating anode Nickel-Zinc batteries for electric vehicles. Support of this effort from DOE is expected in the form of a development contract with ESB.

2. Design Goals and Present State-of-Art Performance

Listed below are the major areas of interest of Nickel-Zinc EV batteries along with the goals desired by DOE in each area. Present estimated state-of-art is indicated in each category.

Characteristic	Goals	Present State-of-Art	
Specific Energy (Whr/kg) @ C/3	> 70	70	(1)
Volumetric Energy (Whr/ℓ) @ C/3	>120	120	(1)
Specific Power (W/kg) (5 sec. ave. @ 80% Disch.)	>125	125	(1)
(20 min. sustained @ C/3 and 50% DOD)	> 45	--	
Cycle Life (80% DOD @ C/3)	>400	75-100	
Wet Life (years)	> 2	2	
Cost ($/kWhr)	< 75	200 (est.)	(2)
Energy Efficiency (%)	> 60	~65	

(1) Obtainable on early cycles only.

(2) 1978 dollars, up to 1000 EV batteries per year

3. Nickel-Zinc EV Battery Performance (Conventional Type)

a) Advantages

Potential High Energy Density and Specific Power

High Voltage per cell (1.60 V average)

b) Disadvantages

Life - Limited by three major factors: separator degradation, shorting by zinc dendrites, capacity fall-off due to shape change of negative electrode.

Charging - Sensitive to overcharge because of tendency to form zinc dendrites during overcharge. Nickel cathodes require overcharge to develop full capacity.

Cost - Tends to be high, especially with the high energy density nickel cathodes (e.g., sintered type) needed to achieve performance.

Maintenance - Frequent water additions necessary due to overcharge requirements of nickel electrode.

c) Electrical Performance

Attached are three figures depicting state-of-the-art nickel-zinc cell (conventional type) electrical performance. Figure 1 is a Ragone plot depicting the relationship of specific power (W/kg) to energy density (Whr/lb). The solid line represents data taken from three sources. The Energy Research data is from ANL-K76-3541-1, Final Report, "Design and Cost Study of Nickel-Zinc Batteries for Electric Vehicle." The Yardney data is from ANL-K76-3543-1, Final Report, "Design and Cost Study Zinc/Nickel Oxide Battery for Electric Vehicle Propulsion." The ESB data is from proprietary data developed during internal R & D programs. For purposes of comparison the Ragone plot obtained from the GRC and CCM data is superimposed as a dotted line. Agreement is fairly close, with the available electrical data indicating a slightly lower energy density at low rates of discharge, but possibly a higher specific power at high rates of discharge. Figure 2 gives typical discharge performance of a Yardney 310 Ahr cell at rates of C, C/3 and C/5. Figures 3 & 4 are discharge characteristics curves and power curves for ESB 25 Ah nickel zinc cells.

All of this information, it must be emphasized, is based on the performance of Ni-Zn cells during early cycles. Presently available "conventional" Nickel-Zinc batteries tend to lose capacity by fading within 50 deep cycles, and could lose as much as 50% of original capacity within 100-150 cycles, depending on the rate of discharge. Cycle life is also dependent upon depth of discharge; however, no definitive data on this is available.

ANL, through its DOE funding, is basing Ni-Zn development on a 25 kWhr battery size. At 30 Whr/lb, battery weight would be about 833 lb and its volume about 6.6 cu ft. Cell capacity is designated at 300 Ahr, giving a battery voltage of about 83.3 volts, or 52 cells in series. If such a battery comprised 1/3 the vehicle weight, a range of about 80-120 miles per charge can be expected, depending on the type of driving cycle used.

RAGONE PLOT Ni-Zn BATTERIES

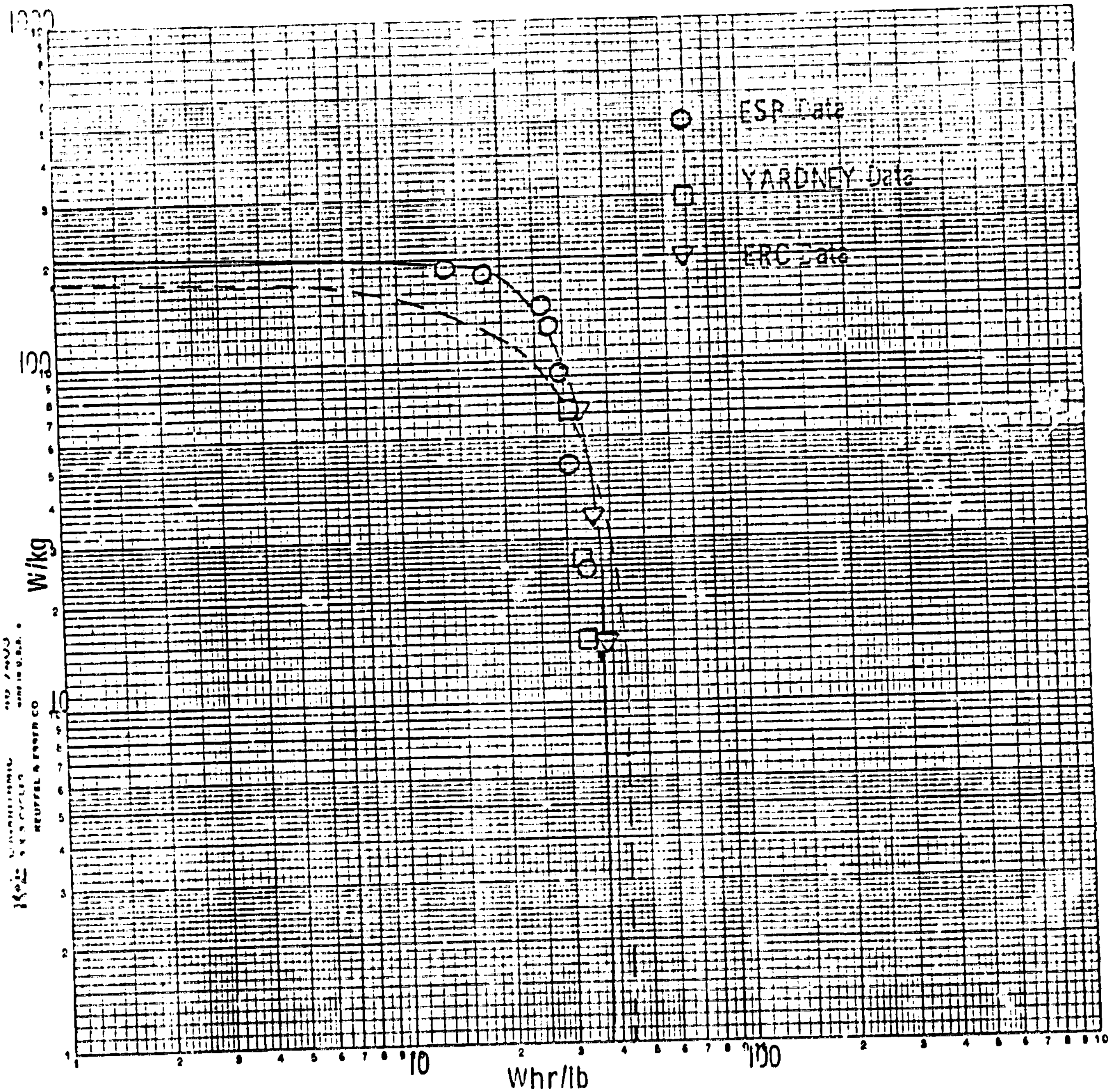


FIGURE I

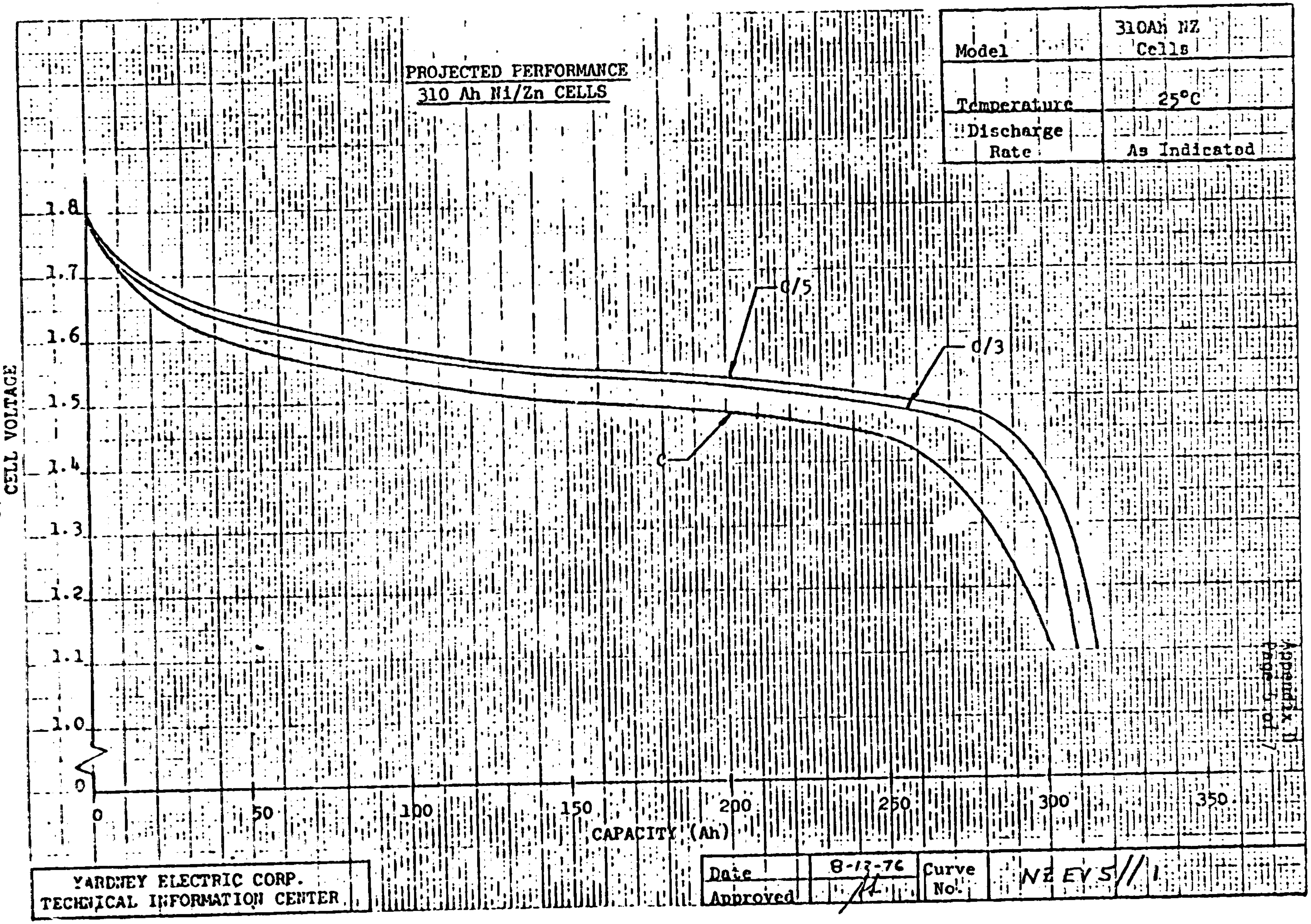

PROJECTED PERFORMANCE
310 Ah Ni/Zn CELLS
Model
310Ah NZ Cells
Temperature
25°C
Discharge Rate
As Indicated
C/5
C/3
C
CELL VOLTAGE
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
0
50
100
150
200
250
300
350
CAPACITY (Ah)
YARDNEY ELECTRIC CORP.
TECHNICAL INFORMATION CENTER
Date
8-13-76
Approved
Curve No.
NZ EV5//1

FIGURE 2

SUPPLEMENT #1 TO

THE ASSESSMENT OF

BATTERY POWER SOURCES

THE

GE PHASE I HYBRID VEHICLE

PREPARED FOR

GENERAL ELECTRIC COMPANY

CORPORATE RESEARCH AND DEVELOPMENT

P.O. A0200-22067

ESB Project 6047

FEBRUARY 16, 1979

PREPARED BY

D. T. Ferrell

ESB TECHNOLOGY COMPANY
YARDLEY, PA.

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At the request of Dr. A. F. Burke on February 12, 1979, we have assembled information on other DOE battery programs, and have provided our assessment of them.

The first group (Pages 1-7) are from DOE/ET-0038 dated October 1978 which is the Program Overview for Energy Storage Systems for FY 1978.

PAN-10 and PAN-4 (Pages 8 & 9) are from a Paul Nelson presentation in May 1978 on the ANL program. This is undoubtedly optimistic. Ford Na/S EV program is on approximately the Mark II schedule EDA $Zn-Cl_2H_2O$ is only a slightly faster track.

The 4 DOE Advanced Battery Programs are:

	5 YR(Tech.)	Probability 10 YR(Comm.)	20 YR (Comm.)
EDA $Zn-Cl_2H_2O$	0.95	0.5	0.75
Ford Na-S (beta alumina)	0.8	0.25	0.5
Dow Na-S (glass)	0.2	0.0	0.2
ANL Li-MS	0.9	0.5	0.75

The probabilities are assessments for EV's, and reflect some pessimism about non-lead-acid EV's in general

Since this document page contains assessments and probabilities of a judgemental nature, further dissemination or discussion of this page outside GE (without express concurrence of ESB Inc. is requested. Information contained on the balance of this supplement are not subjected to this restriction.

TABLE 1. MAJOR PROJECT LISTING

PROJECT	NAME AND LOCATION OF PROJECT MANAGER	PERFORMING ORGANIZATION	BA ($K) FUNDING FY 1978	($K) TEC
BATTERIES AND ELECTROCHEMICAL SUBPROGRAM				
Near-Term Batteries				
Electric Vehicle Batteries* (Lead/Acid, Nickel/Iron, Nickel/Zinc)	N.P. YAO, ANL	ANL and eight industrial subcontractors	5,700	46,700
Adv. Lead/Acid Batteries for Load Leveling	H. Shimotake, ANL	RFP	300	5,000
Advanced Batteries in Engineering Development* (Li/S, Na/S, Zn/Cl)	P. Nelson, ANL/K. Klunder, DOE	Ford, Dow, EDA, ANL (with five industrial subcontractors)	10,700	101,000
Solar Applications	N.P. YAO, ANL	ANL and TBD	500	5,000
Industrial Electrolytic Processes*	G. Cook, ANL	Diamond Shamrock, U. of Illinois Argonne National Lab	1,250	12,000
CHEMICAL AND THERMAL SUBPROGRAM				
Hydride Storage Vessel Development	F. Salzano BNL	INCO, Billings, Foster-Wheeler	850	15,000
Electrolyzer Development for H_2 Production*	F. Salzano BNL	GE, TELEDYNE	1,300	12,000
Seasonal Storage in Aquifer for Building Heating and Cooling	H. Hoffman ORNL	Desert Reclamation Auburn University Texas A&M	400	5,000
Retrofit System for Industrial Process Heat Recovery	H. Hoffman ORNL W. Masica NASA/Lewis	Rocket Research, Boeing, Martin-Marietta, Westinghouse	500	6,000
Chemical Heat Pump for Building Heating and Cooling	W. Wilson SLL	Martin-Marietta, Rocket Research, EIC, Chemical Energy Specialists	400	5,000

*Key Project

TABLE 1. MAJOR PROJECT LISTING

(Continued)

PROJECT	NAME AND LOCATION OF PROJECT MANAGER	PERFORMING ORGANIZATION	BA ($K) FUNDING FY 1978	($K) TEC
MECHANICAL AND MAGNETIC SUBPROGRAM				
Mechanical Energy Storage for Electric and Hybrid Vehicles*	Thomas Barlow Livermore, Calif.	LLL and Industry	1,800	7,800
Superconducting Magnetic Energy Storage for Transmission Stability	John Rogers Los Alamos, N. Mex.	LASL and Industry	1,050	5,100
No-Oil Compressed Air System Development	Walter Loscutoff Richland, Wash.	PNL and Industry	160	10,000
TECHNICAL AND ECONOMIC ANALYSIS SUBPROGRAM				
STOR R&D Program Evaluation and Review System	L. Holt DOE	NAS, LLL, LeHigh Univ., U. of Maryland	950	3,000
Energy Storage for National Transportation	E. Behrin LLL	LLL-lead lab, ANL, BNL, LBL, Battelle (Industrial Subcontractors)	500	1,250
Energy Storage for Solar Systems	L. Framan NASA-JPL	NASA-JPL lead lab (DOE Labs, Industrial Subcontractors)	700	2,000
Decentralized Storage Systems Studies	J. Asbury ANL	ANL-lead lab (Industry and University Subcontractors)	900	3,500

*Key Project

TABLE 2. COMMERCIAL TECHNOLOGY TIMETABLE

SUBPROGRAM	1980-1984	1985-1990	AFTER 1990
BATTERIES AND ELECTROCHEMICAL SYSTEMS	● NEAR TERM ELECTRIC CARS ○ DISPERSED UTILITY LOAD LEVELING	● ADVANCED ELECTRIC CARS ● ADVANCED BATTERIES FOR LOAD LEVELING	● SOLAR ELECTRIC STORAGE ● IMPROVED ELECTROCHEMICAL PROCESSES
CHEMICAL AND THERMAL SYSTEMS	○ H_2 FOR CHEMICAL FEEDSTOCK ● SOLAR SEASONAL HEATING AND COOLING	○ H_2 SUPPLEMENTATION OF NATURAL GAS ○ CHEMICAL HEAT PUMPS WITH STORAGE ○ THERMAL STORAGE FOR LOAD LEVELING	○ H_2 AND THERMOCHEMICAL STORAGE FOR SOLAR ○ H_2 FOR VEHICLES
MECHANICAL AND AND MAGNETIC SYSTEMS	● UTILITY STORAGE (UPH CAES) ○ FLYWHEEL REGENERATIVE BRAKING		○ ADVANCED CAES ○ SMES FOR UTILITY LOAD LEVELING

● FUNDS LIMITED
○ TECHNOLOGY LIMITED

Technologies to serve both mobile and stationary applications are being developed. Development progress in the two areas can be measured against the goals stated below.

Mobile Storage Goals

- Batteries for transportation having an energy density of 140 watt-hours per kilogram, a peak power capability of 200 watts per kilogram, and capital costs less than $40 per kilowatt-hour
- Flywheel regenerative braking systems resulting in a 30 percent energy savings when incorporated into battery-powered vehicles for city driving
- Hydride materials for hydrogen-fueled vehicles that store twice as much hydrogen as iron titanium hydride, with an energy density of more than 800 watt-hours per kilogram

Stationary Storage Goals

- Battery, chemical, thermal, and mechanical storage systems having appropriate characteristics for use in smoothing the intermittent availability of power from solar and wind energy systems

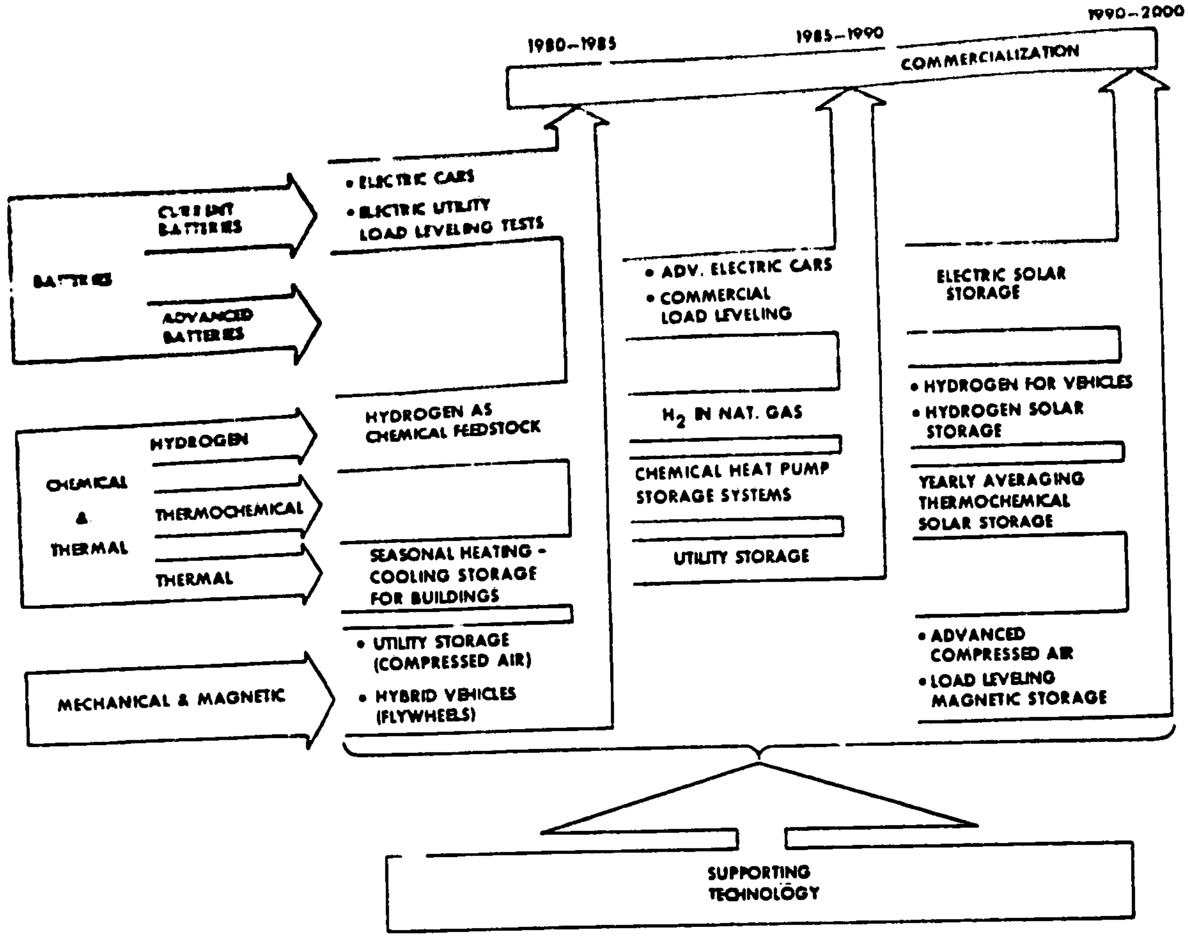


Figure 4. Storage Delivery Strategy Diagram

Technology Options for Energy Storage

Different applications require that different amounts of energy be stored for various duty cycles. A spectrum of technologies is being developed to meet these different needs. As shown in Table 2, some of these technologies are expected to be commercialized within the next decade while others will not be commercially available until the year 2,000 or later.

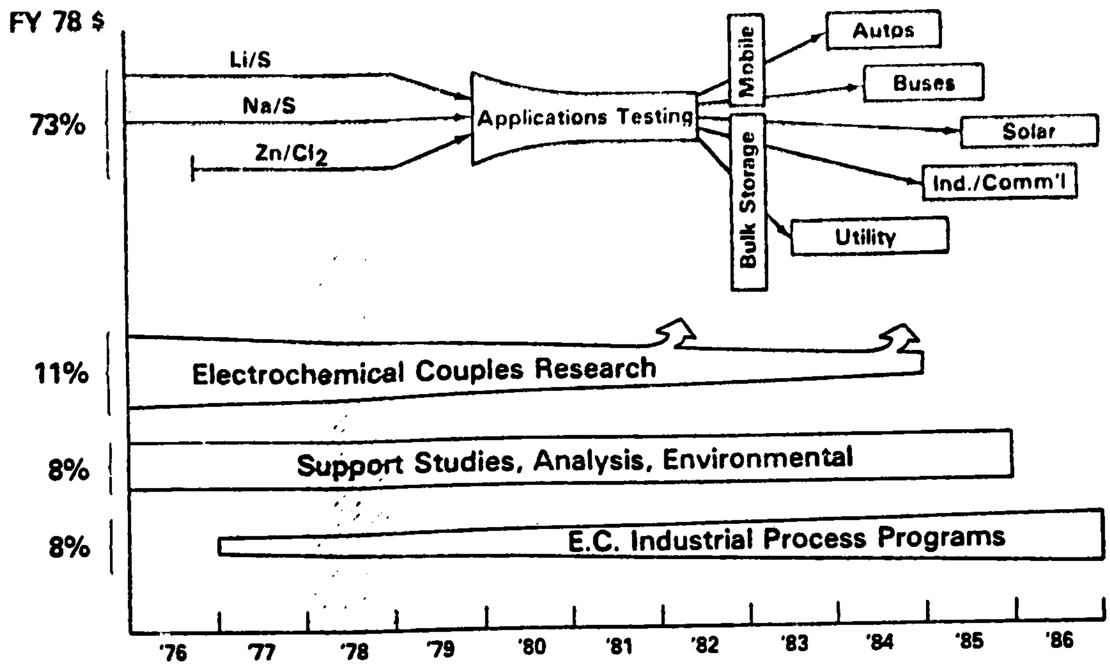


Figure 12. Advanced Battery Program Thrust and Emphasis

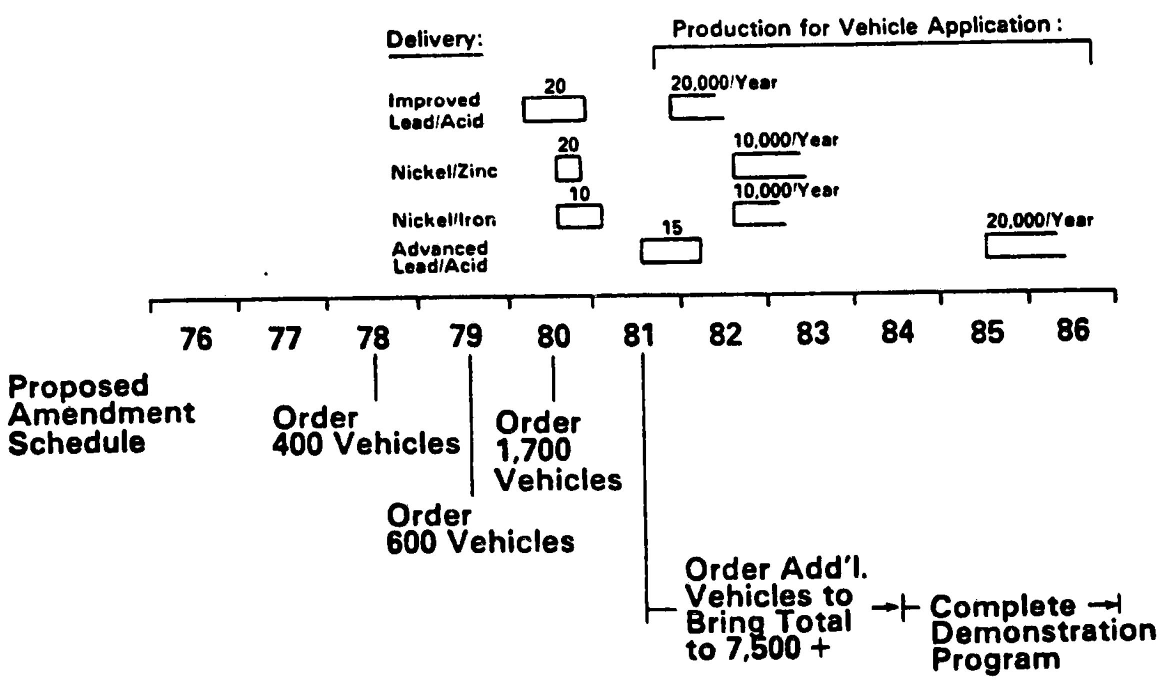


Figure 13. Near Term Battery Program

- Develop and test improved near-term batteries to support vehicle buys legislated by the Electric and Hybrid Vehicle Demonstration Act.

- Start advanced lead/acid battery development for near-term load leveling.

Figure 15 shows the major milestones of the batteries and electrochemical systems subprogram for FY 1978 through FY 1982.

The subprogram is divided into the areas of:

- Near Term Battery Program

- Advanced Batteries in Engineering Development

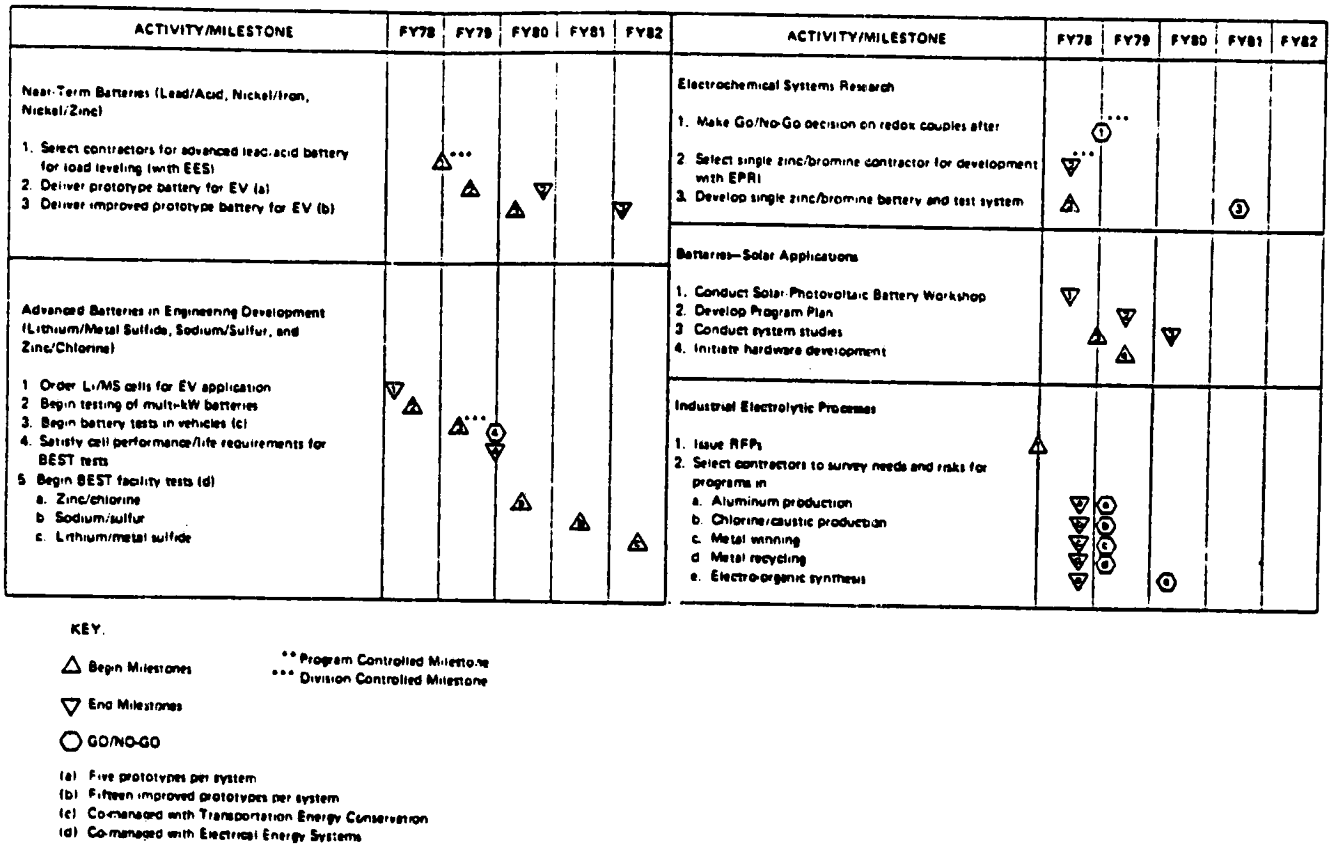


Figure 15. Milestone Chart

TABLE 4. STATUS AND GOALS VEHICLE BATTERIES

Battery	Status		Development FY 1978		Goals*		
	Wh/kg	Cycles	Wh/kg	Cycles	Year	Wh/kg	Cycles
Near Term Batteries							
Lead/Acid	30	300	35	300	1980	40-50	600-800
Nickel/Iron	44	1500	50	1500	1980	60	2000
Nickel/Zinc	60	300	70	350	1981	75	800
Advanced Batteries							
Zinc/Chlorine	70	300	80	400	1980	110	1000
Sodium/Sulfur	80	300	100	400	1981	140	1000
Lithium/Metal-Sulfide	80	400	90	500	1981	140	1000

*Goal dates for near term batteries apply to full size vehicle batteries available in quantities required to support the EHV Demonstration Act. Advanced battery goal dates refer to first test module in laboratory.

PAN-10

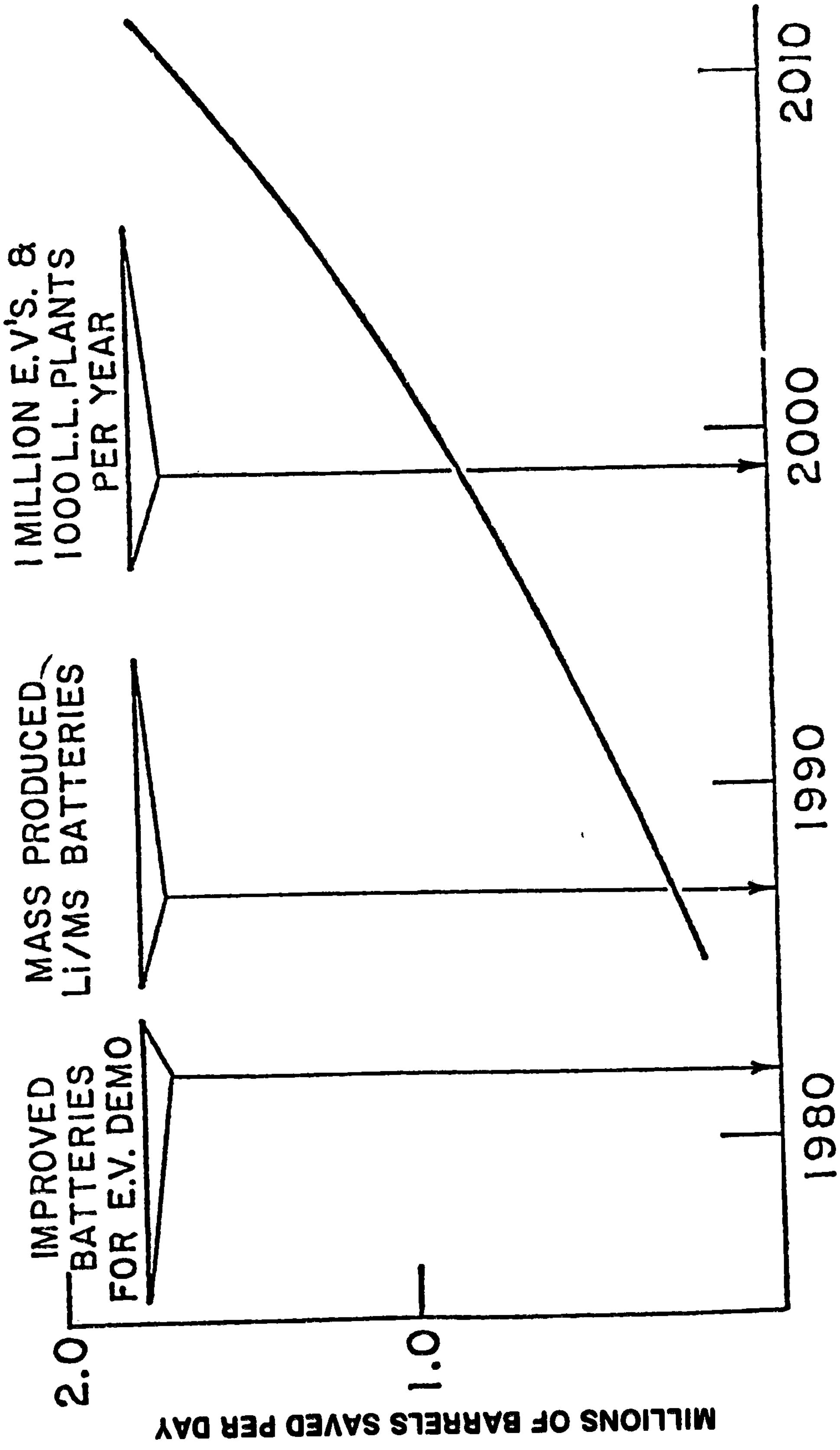
STAGES IN DEVELOPMENT OF
LITHIUM/METAL SULFIDE VEHICLE BATTERIES
FULL-SCALE BATTERY PROJECTS

Stage	Purpose	Demonstration of Goals[a]
Mark I	First Test in Vehicle Eagle-Picher	1979
Mark II	Commercially Viable Prototype EP and Gould Phase I Contractors	1981 — 1983
Mark III	High-Performance Commercial Battery	1983 — 1986

[a]Date of demonstration is dependent on funding rate.

OIL SAVED THROUGH THE USE OF BATTERIES
FOR ELECTRIC VEHICLES AND UTILITY LOAD-LEVELING

PRODUCTION SCHEDULE



CUMULATIVE SAVINGS TO YEAR 2020
OIL SAVED 4.7 BILLION bbls
VALUE $ 92 BILLION

SUPPLEMENT #2 TO

THE ASSESSMENT OF BATTERY POWER SOURCES THE GE PHASE I HYBRID VEHICLE

PREPARED FOR

GENERAL ELECTRIC COMPANY

CORPORATE RESEARCH AND DEVELOPMENT

P.O. A0200-22067

ESB PROJECT 6047

MARCH 1, 1979

PREPARED BY

E. Pearlman

G. S. Hartman

ESB TECHNOLOGY COMPANY
YARDLEY, PA.

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SUPPLEMENT 2

NICKEL HYDROGEN BATTERIES

At the GE Phase I Hybrid Vehicle program review on February 20, 1979, Mr. E. Rowland requested an assessment on the nickel hydrogen battery system as applicable to E.V. application

Attached are Supplement #2, pages 2 to 6 describing the $Ni\text{-}H_2$ system.

In addition pages 99 & 100 are reproduced from the paper by Sidney Gross, Energy Conversion, Vol. 15, pp. 95 - 112 (1976) and shown as pages 5 and 6.

None of the information provided in Supplements 1 or 2 modifies the recommendations made in our original report.

SUPPLEMENT 2

NICKEL HYDROGEN BATTERIES

(1) The nickel-hydrogen system has been investigated and used mainly on satellite battery applications. Some have flown successfully on satellites, coupled with charging from solar panels. Their best performance characteristic is the increase in cycle life over Ni-Cd batteries, which suffer capacity losses with cycling due to Cd passivation. The attached material (from Kirk-Othner, Encyclopedia of Chemical Technology, Vol. 3, Third Ed. 1978) gives some of the available data on Ni-H_2 batteries.

(2) Recent work which has been reported by companies such as EIC, HAC and COMSAT indicate certain changes (improvements?) in the technology. Operating pressures have increased to 34-68 atm., in an attempt to increase energy density and discharge rate capability. In addition, common pressure vessels have been experimentally tried. While these improvements have increased both energy density and discharge rate capability, the high H_2 pressures have also resulted in an increased rate of self-discharge. In addition, the common pressure container introduces the problem of capacity rundown caused by parasitic currents. On one test a 4-cell battery was operated at about 30 atm in a common pressure vessel. In 72 hours capacity fell from 8.8 Ahr to 5.6 Ahr, while pressure fell from 400 psig to 300 psig. This loss corresponds to a rate of over 10% per day.

(3) The use of the Ni-H_2 system in EV applications is not indicated at this time because of these important limitations:

3.1 Pressure Vessel Construction - Present technology requires that each cell of the battery, or at best sections of several cells, be contained in pressure vessels holding up to 1000 psig of hydrogen. This in itself is so dangerous that it alone probably eliminates the system from consideration.

3.2 Cost Considerations - The battery has all of the inherent costs of satellite type sealed, sintered, nickel cadmium batteries, plus the additional costs of high pressure battery containers, and the use of platinum doped electrodes for hydrogen recombination.

3.3 Electrical pefformance - Charged stand losses are too high for most EV applications, and in addition there is a question about maximum specific power available. Most data presented does not indicate discharge rates greater than C/2.

(4) The possibility exists for hydrogen storage utilizing surface adsorbtion or chemical hydrides. There is some work going on in this area, but none has reached the level of cell or battery demonstration. If there is to be a Ni-H_2 EV battery this could be the only way to solve the high pressure storage problem.

Nickel-Hydrogen Cells. In the mid 1970s nickel-hydrogen cells were developed in the United States (79) and in Europe to overcome some of the problems associated with deep cycle nickel–cadmium, long-life cells for space satellite use. The memory effect (80) of the cadmium electrode was eliminated and gravimetric energy density improved. The overall electrochemical reaction is simple:

$$Ni(OH)_2 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} NiOOH + \tfrac{1}{2} H_2$$

However, the generation and migration of water in the half-cell reactions must be considered in the cell design.

At the nickel electrode:

$$Ni(OH)_2 + OH \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} NiOOH + H_2O + e^-$$

At the hydrogen electrode:

$$H_2O + e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} \tfrac{1}{2} H_2 + OH^-$$

Hydrogen is present in the gaseous state, and the cells operate at a much higher pressure range 304–2030 kPa (3–20 atm) than Ni–Cd cells 0–304 kPa (0–3 atm). Cells are designed as pressure vessels and are cylindrical in shape with hemispherical caps. Electric terminals are made with ceramic-to-metal seals in the end caps. A cutaway view of a typical construction is shown in Figure 14.

The positive electrodes are of a conventional sintered type. The hydrogen reacting (negative) electrode usually consists of a Teflon-bonded platinum black layer and a porous Teflon layer pressed into a fine mesh nickel screen.

Typical voltage performance discharge curves are given in Figure 15.

Figure 14. Cutaway view of a typical construction of a nickel–hydrogen cell.

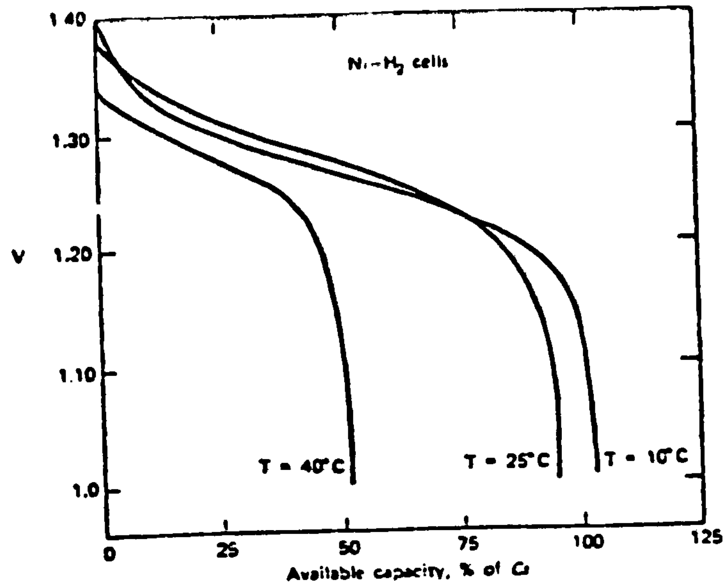


Figure 15. Typical voltage performance discharge curves of a nickel-hydrogen cell. Discharge rate, C/2 h; Charge rate, C/5 h; Cs = capacity at C/5 h and 20°C; C = capacity.

Nickel-hydrogen battery

The nickel-hydrogen system has an open circuit potential of 1·358 V and a theoretical energy density of 177 W hr/lb. This is a recently developed system [63–66] but the technology is advancing rapidly because the nickel electrode is well developed from nickel–cadmium battery technology, and the hydrogen electrode is well developed from hydrogen–oxygen fuel cell technology. The Teflonated hydrogen electrode negative functions best with platinum catalyst, but nickel is satisfactory for electric vehicle applications, and is used in Russian designs [65]. Both electrodes are known to be long-lived, so very long operating lifetimes are expected with this system. An energy density of 25 W hr/lb has been achieved on prototype cells, and design studies show up to 40 W hr/lb should be attainable. Power density of 40 W/lb has been realized, and could be increased to 200 W/lb on an optimized design. 20 W-H/lb

A nickel–hydrogen battery consists of a series stack of nickel and hydrogen electrodes installed inside a pressure vessel filled with hydrogen gas. The electrodes are separated by gas diffusion screens, but the hydrogen gas need not be isolated from the nickel electrodes since they will not react chemically. The battery operates positive-limited, and is completely sealed. Figure 7 shows a typical battery module design [64]. Except for the pressure vessel, no costly materials are used. Typical operating characteristics of a single cell are shown in Fig. 8 and are

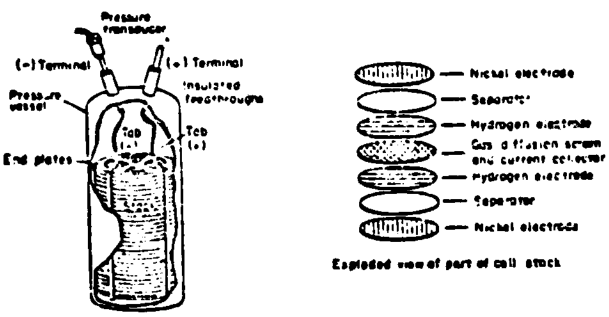
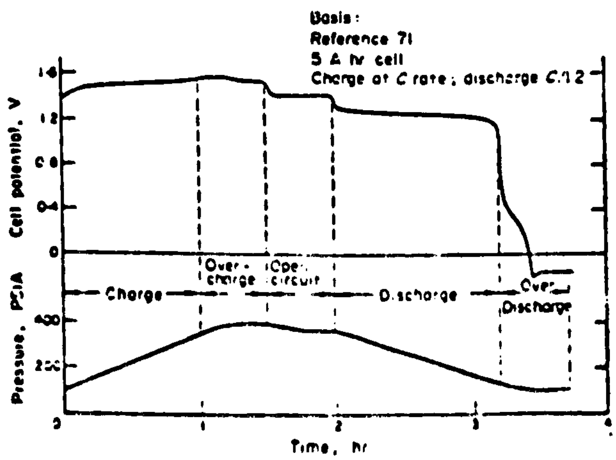


Fig. 7. Typical nickel-hydrogen battery design.



seen to be comparable to nickel cadmium cell performance.

An important attribute of the nickel-hydrogen system is that it is inherently protected against damage by reversal, permitting the full capacity of the battery to be used. Hydrogen pressure drops to approx. 100 psi during continuous reversal. Also significant is the ability of the system to tolerate overcharge without ill effect, though suitable means of heat removal must be provided. Hydrogen pressure increases to a maximum of 400–500 psi during continuous overcharge.

The major disadvantage of the nickel-hydrogen system is the need for a pressure vessel to contain the hydrogen, which comprises a significant share of the battery weight. Structural safety factors will have to be relatively high for commercial applications, limiting the overall energy density. For example, it is calculated [66] that a 1000 W battery for traction applications would deliver 35 W hr/lb with a titanium pressure vessel, or 30 W hr/lb with an Inconel pressure vessel. Even with the lower value, this is quite attractive for electric vehicles in view of the good electrical performance and expected long life.

A possible improvement to the nickel-hydrogen battery would be development of a satisfactory means of storing hydrogen in solids. Metal hydrides are able to store hydrogen even more compactly than liquid hydrogen. Using this principle, an electrochemically reversible hydrogen electrode has been developed in which the hydrogen is stored on interstitial sites of a metal lattice, using Ti_2Ni and TiNi intermetallic phases [67]. The electrode is capable of very high energy density, and conceivably could eliminate or minimize the need for a pressure vessel with the nickel-hydrogen battery.

PULSED TESTS OF LEAD-ACID BATTERIES
ESB Technology Corporation
June 1979

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Battery: PV-23

Pulse Current: 300 A

Ah out at Beginning of Pulse	% of Ah at 60 A	Voltage During Pulse(*)	Volts at 60 A After Pulse	Wh out After Pulse
12.1	7.1	5.400/5.365	6.000	73
31.4	18.5	5.360/5.330	5.950	188
44.8†	26.3	5.285/5.255	—	267
46.1†	27.1	5.325/5.265	—	274
47.4†	27.9	5.355/5.265	5.890	281
67.1	39.5	5.190/5.190	5.835	396
80.7	47.5	5.115/5.115	5.775	474
100.2†	58.9	5.030/4.970	—	586
101.4†	59.7	5.045/4.985	—	592
102.7†	60.0	5.010/4.250	—	598
110.2	64.8		5.675	640

(*)15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

†Pulses repeated with open circuit pause between each one

Battery: PV-23

Pulse Current: 400 A

Ah out at Beginning Pulse	% of Ah at 60 A	Voltage During Pulse*	Volts at 60 A After Pulse	Wh out After Pulse
12.0	7.1	5.175/5.145	6.060	73
31.9	18.8	5.140/5.110	6.010	192
45.9†	27.0	5.065	5.955	273
47.6†	28.0	5.110/5.050	--	282
49.3†	29.0	5.110/5.045	5.895	291
69.4	40.8	4.970/4.940	5.845	407
83.3	49.0	4.885/4.855	5.770	487
103.1†	60.6	4.710/4.675	--	600
104.9†	61.7	4.76 /4.670	--	608
106.5†	62.6	4.700/4.640	--	616
114.3	67.2		5.675	659

*15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

†Pulses repeated with open circuit pause between each one

Battery: PV-23

Pulse Current: 400 A

Ah out at Beginning Pulse	% of Ah at 60 A	Voltage During Pulse*	Volts at 60 A After Pulse	Wh out After Pulse
12.1	7.1	4.985/4.955	6.045	73
32.2	18.9	4.910/4.880	6.015	192
46.5†	27.4	4.810/4.780	--	276
48.7†	28.6	4.875/4.755	--	286
50.8†	29.9	4.895/4.740	5.905	296
71.1	41.8	4.660/4.615	5.815	413
85.2	50.1	4.575/4.515	5.765	493
105.0†	61.8	4.395/4.32	--	608
107.6†	63.3	4.405/4.285	--	617
109.7†	64.5	4.395/4.245	5.670	626
118.0	69.4		5.670	669

*15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

†Pulses repeated with open circuit pause between each one

Battery: EV-106

Pulse Current: 400 A

Ah out at Beginning Pulse	% of Ah at 60 A	Voltage During Pulse*	Volts at 60 A After Pulse	Wh out After Pulse
11.9	8.8	5.07	6.025	73
31.6	23.4	5.00	5.960	189
45.4†	33.6	4.97/4.92	--	270
47.0†	34.8	4.95/4.92	--	278
48.8†	36.1	4.92/4.89	5.890	286
68.4	50.7	4.77/4.74	5.790	400
82.2	60.8	4.62/4.56	5.700	478
101.9†	75.5	4.30/4.18	--	588
103.6†	76.7	4.29/4.11	--	595
105.2†	77.9	4.22/4.05	5.520	602
112.9	83.6		5.485	642

*15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

†Pulses repeated with open circuit pause between each one

Battery: EV-106

Pulse Current: 300 A

Ah out at Beginning of Pulse	% of Ah at 60 A	Voltage During Pulse*	Volts at 60 A After Pulse	Wh out After Pulse
12.0	8.8	5.375	6.045	74
31.5	23.3	5.350/5.32	5.995	189
44.8†	33.2	5.310/5.280	--	269
46.1†	34.1	5.300/5.280	--	276
47.4†	35.0	5.300/5.270	5.920	283
66.7	49.4	5.190/5.160	5.870	396
79.9	59.2	5.09	5.810	472
99.2†	73.5	4.955/4.925	--	--
100.6†	74.5	4.960/4.900	--	--
101.8†	75.4	4.935/4.875	5.675	596
109.0	80.7		5.675	637

*15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

†Pulses repeated with open circuit pause between each one

Battery: EV-106

Pulse Current: 500 A

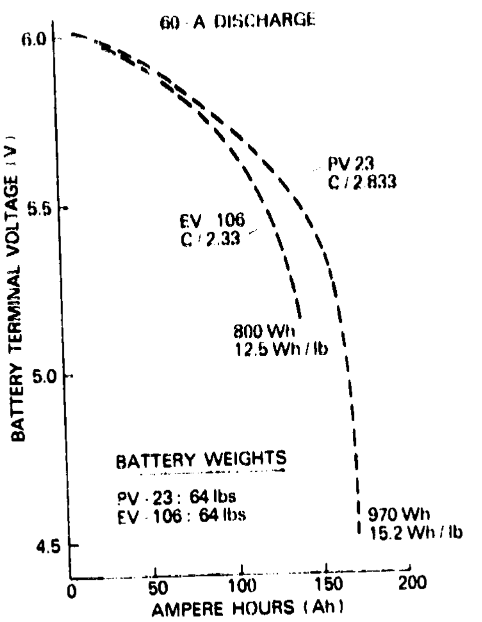
Ah out at Beginning Pulse	% of Ah at 60 A	Voltage During Phase*	Volts at 60 A After Pulse	Wh out After Pulse
12.0	8.8	4.785	6.020	72
32.4	24.0	4.720/4.690	5.965	192
46.5†	34.4	4.650/4.620	--	--
48.6†	36.0	4.640/4.580	--	--
50.7†	37.5	4.610/4.550	5.875	293
70.8	52.4	4.440/4.385	5.765	408
84.9	62.3	4.290/4.200	5.695	487
105.3	78.0	3.985/3.955	--	600

*15 s pulse; a/b : a-voltage at 1 s, b-voltage at 15 s

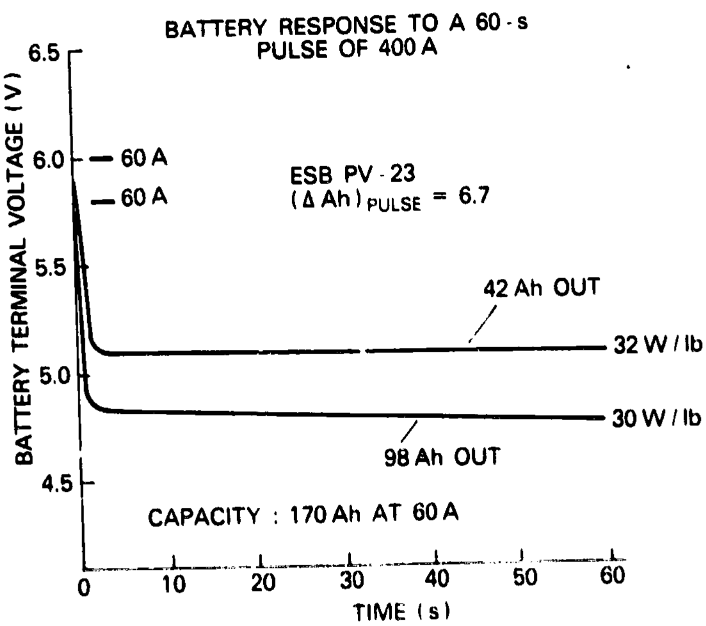
†Pulses repeated with open circuit pause between each one

Note:

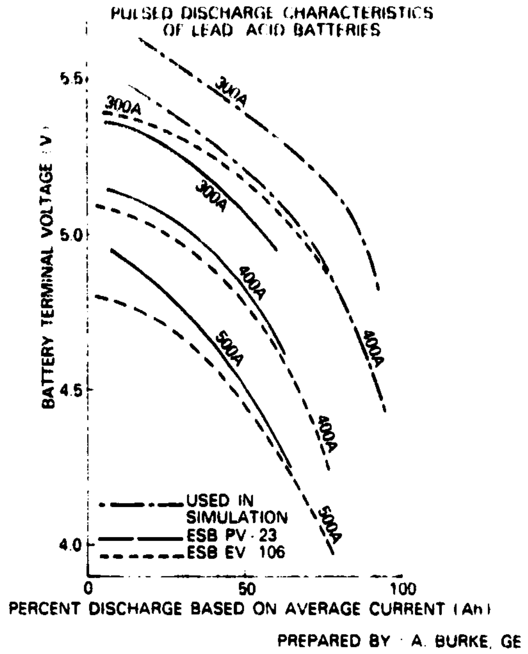
The following graphs were prepared by Dr. A.F. Burke, General Electric Corporate Research and Development. They are included in the Assessment of Battery Power Sources for completeness.

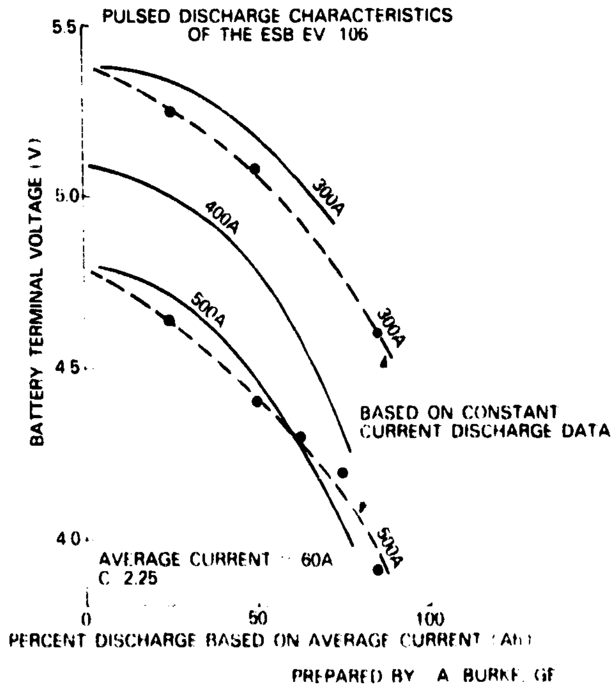


PREPARED BY : A. BURKE, GE

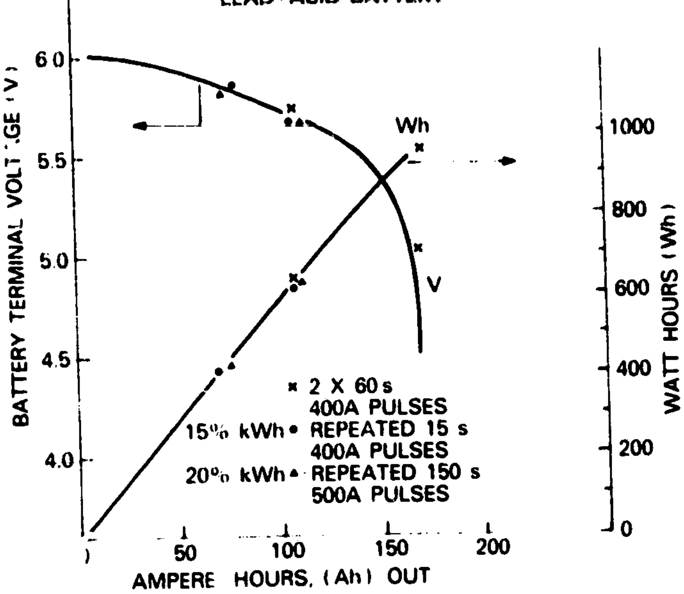


PREPARED BY : A. BURKE, GE


PULSED DISCHARGE CHARACTERISTICS
OF LEAD ACID BATTERIES
BATTERY TERMINAL VOLTAGE (V)
5.5
5.0
4.5
4.0
300A
300A
300A
400A
400A
400A
500A
500A
USED IN SIMULATION
ESB PV-23
ESB EV 106
0
50
100
PERCENT DISCHARGE BASED ON AVERAGE CURRENT (Ah)
PREPARED BY A. BURKE, GE

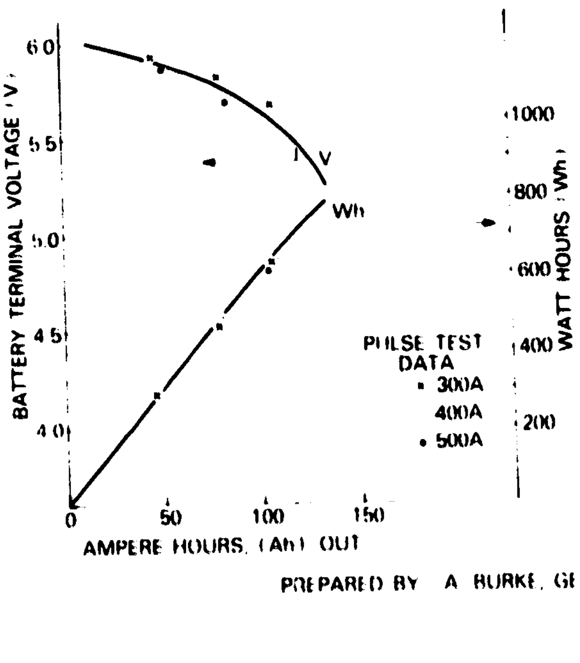

PULSED DISCHARGE CHARACTERISTICS
OF THE ESB EV 106
BATTERY TERMINAL VOLTAGE (V)
5.5
5.0
4.5
4.0
300A
300A
400A
500A
500A
BASED ON CONSTANT
CURRENT DISCHARGE DATA
AVERAGE CURRENT 60A
C 2.25
0
50
100
PERCENT DISCHARGE BASED ON AVERAGE CURRENT (Ah)
PREPARED BY A. BURKE, GE

CONSTANT CURRENT 60A
DISCHARGE OF THE ESB PV 23
LEAD ACID BATTERY



PREPARED BY : A. BURKE, GE

DISCHARGE CHARACTERISTIC OF THE
ESB EV 1?6 AT 60A



PREPARED BY A. BURKE, GE

Section 3

VEHICLE TECHNOLOGY

GENERAL ELECTRIC

WORK STATEMENT

Triad Services, Incorporated
32049 Howard Street
Madison Heights, MI 48071

INTRODUCTION

Contract NO. 955190 between California Institute of Technology Jet Propulsion Laboratory and General Electric Company covers a program entitled "Phase I of the Near-Term Hybrid Passenger Vehicle Development Program" under which studies shall be conducted leading to a preliminary design of a hybrid passenger vehicle that is projected to have the maximum potential for reducing petroleum consumption in the near-term (commencing in 1985). Effort under Contract 955190 is being conducted pursuant to an Interagency Agreement between the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) and in furtherance of work under Prime Contract NAS7-100 between NASA and the California Institute of Technology. This work statement covers vehicle technology under General Electric Purchase Order A02000-220147.

SCOPE OF WORK

In support of General Electric Corporate Research and Development's work under Contract 955190, the Subcontractor shall furnish the necessary personnel, materials, services, facilities, and otherwise do all things necessary for or incident to the performance of the following tasks.

1. Provision of the following with respect to the Reference Conventional ICE vehicle.
   - Consultation to assist in its selection
   - Weight and cost information on key components
   - Performance information on auxiliaries, such as power steering, power brakes, air conditioning, lighting and electrical accessories, heating and ventilating
2. Consultation on selection of preferred passenger compartment heating procedure for hybrid vehicle considering such approaches as:
   - Waste heat from the engine
   - Thermal energy storage
   - Auxiliary burner
3. Consultation on air conditioning for the hybrid vehicle, especially methods of taking advantage of the reduced input speed variation for the hybrid as compared with the conventional ICE vehicle.

4. Trade-off studies of power assist systems (power steering and power brakes) to determine the preferred approach and performance for the hybrid vehicle.

5. Consultation and recommendations on specification of tire drag aerodynamic drag and aerodynamic frontal area for both:

   - The conventional ICE vehicle

     <u>AND</u>

   - The hybrid vehicles

6. Recommended weight and/or power scaling factors to be applied in building up the hybrid vehicle around the seating package of the reference conventional ICE vehicle.

7. Packaging studies of various hybrid configurations, using the reference ICE vehicle as a base, including styling consideration.

8. Layouts of the vehicle embodying the preferred hybrid configuration.

9. Vehicle Dynamics - For the preferred configuration, idenification of dynamic design requirements and analysis as required to assure adequate performance in the following areas:

   - Handling - both linear and nonlinear ranges
   - Brake system, including consideration of regenerative braking and front vs. rear wheel braking regeneratively

10. Structural Considerations - For the preferred configuration, analysis as required to assure adequate performance in the following areas:

    - Local stresses and overall stiffness
    - Vehicle structural crashworthiness (Occupant protection will be assumed to be adequate, based upon reference conventional ICE occupant protection, if vehicle is crashworthy)

11. Safety - Indentification of applicable NHTSA and FMVSS safety recommendations and requirements and definition of design approaches which will satisfy those requirements, together with rationale thereof.

12. Cost - Consultation on estimating production costs of major elements of the hybrid vehicle structure and auxiliaries.

NOTE WITH RESPECT TO SUBCONTRACTOR'S DATA

It is understood that all data in the Subcontractor's reports, furnished by the Subcontractor to General Electric Corporate Research and Development hereunder, may be furnished to the California Institute of Technology Jet Propulsion Laboratory and the Department of Energy and the National Aeronautics and Space Agency with no restrictions.

DEVELOPMENT OF WEIGHT PROPAGATION FACTORS

I PURPOSE

The purpose of this study was to develop a set of equations which would predict with some accuracy the gross vehicle weight of proposed hybrid vehicles for the purposes of trade-off analysis.

II METHOD

Detail weight breakdowns for thirteen different vehicles were analyzed to attempt to establish relationships between vehicle gross weight, number of passengers, engine size, and wheel-base and certain component weights. Algebraic functions were derived for these relationships utilizing the least squares technique.

Vehicle weights were divided into 29 categories for the purpose of analyzing the data. Weights of each category for the 13 vehicles, where data formats allowed, were studied in order to determine if functional relationships existed between the weights and the independent parameters stated earlier.

III VEHICLES STUDIED

The 13 vehicles studied and their gross weights are listed below:

VEHICLE	GVW
. Dasher 4-Dr	2923
. Fiat 124	2786
. Fiat 128	2610
. Subaru DL	2410
. Chevette	2781
. Oldsmobile F-83 (1972)	4460
. Chevrolet Corvette	3711
. Chevrolet Vega	3097
. Ford Pinto	3276
. Chevrolet Chevelle (1975)	4443
. Chevrolet Camaro (1974)	4287
. Volkswagen Rabbit	2583
. Buick Regal (1978)	4034

IV DEFINITIONS:

W_c = Vehicle curb wt-lbs.
W_g = Vehicle gross wt-lbs.
P = Number of vehicle passengers

L = Vehicle wheelbase - inches
F = Fuel system capacity - gallons
D = Engine displacement - cubic inches

V RESULTS

The following relationships have been developed for the various vehicle elements.

A Gross Vehicle Weight Related Elements.

SYSTEM	RELATIONSHIP
Structural	$.0437\ Wg + .0000356\ Wg^2$
Bumpers	$.00147Wg + .0000101\ Wg^2$
Suspension	$.02526Wg + .00000736Wg^2$
Wheels & Tires	$20 + .04666Wg$
Brakes	$9.2 + .02368\ Wg$
Tools	$.00281\ Wg$
TOTAL	$29.2 + .14358\ W + 5.3\ W^2 \times 10^{-5}$

B Engine Displacement Related Items.

Engine & Transmission (including fluids)	$290 + .91D$
Exhaust System	$9 + .19D$
Cooling SYstem	$24 + .08D$
TOTAL	$323 + 1.18D$

C Number of Passenger Related.

Seats & Related	23.2P

D Wheelbase Related. (not glass)

Skins	1.4L

E Fuel Capacity Related.

Fuel System (inc. evap. emission control)	1.53F

F Insensitive Components.

Certain items are relatively insensitive to any of the variables considered in the context of this program. These items deal primarily with human factors (ie elements designed to tolerate loads supplied by the driver).

Those items which will be considered fixed in weight are listed below:

Doors (4 Dr) & Deck	174.0	
Exterior Trim	4.5	
Instrument Panel	20.0	
Interior Trim	60.0	
W/S Wipers	7.6	
Fixed Glass	48.0	(windshield plus rear window)
Park Brake	5.1	
Brake Actuation	5.3	
Brake Hydraulics	15.8	
Controls	9.8	
Power Strg.Gear	30.6	
Steering Linkage	19.8	
Strg.Col. & Wheel	16.6	
Hydraulics	14.7	
Acc. Electrical	59.5	
Heater	15.5	
Restraint SYstem	31.8	
Air Conditioner	126.0	
TOTAL	664.6 lbs	

G Summary

Totalling all of these functions, a relationship can be written for the curb weight of a vehicle.

$$Wc = 1017 + .144\ Wg + 5.3 \times 10^{-5}\ Wg^2$$
$$+ 1.18D + 2[illegible].2P + 1.4L + 1.53F$$

Substituting $Wg = Wc + \text{payload}$

and $K = 1017 + \text{payload}$

where: Payload = luggage + passenger load

+ max fuel load + battery load + motor wt.

+ control weight

and $K1 = K + 1.18D + 23.2P + 1.4L + 1.53F$

then: $6.3 \times 10^{-5}\ Wg^2 + .856\ Wg + K1 = 0$

Solving for Wg

$$Wg = \frac{.856 - \sqrt{.733 - (21.2 \times 10^{-5})\ K1}}{10.6 \times 10^{-5}}$$

As a check, substituting the appropriate values for the reference vehicle.

$K = 1017 + 750(\text{pass}) + 200(\text{lugg.}) + 108\ (\text{fuel})$

$= 2075$

$K1 = K + 1.18(200) + 23.2(5) + 1.4(108.1) + 1.53(18.1)$

$= 2607$

$Wg = 4069$

Wc (calculated) = 4069-1058 = 3011 pounds

which compares with an actual curb weight of 3084 pounds.

VI PROJECTIONS OF FUTURE PRODUCTION VEHICLE WEIGHTS.

As a result of some conversations with knowledgeable people within the automobile industry, it was the consensus of opinion that a reduction in vehicle weight by 1985 will not exceed 10% to 12% for the same sized vehicle compared to 1979 vehicles. This weight reduction will come from basic redesign of components with the use of more specialized parts (less commonality across vehicle lines) rather than by the substitution of other materials for any fundamental parts.

The reasons for not shifting to aluminum or plastic components

in lieu of steel are:

1) Cost effectiveness [$1.00 + per pound penalty].

2) Requirement for significant investment in tooling and equipment.

3) Inadequate supply of aluminum or resin products to meet potential automotive requirements.

VEHICLE DRAG PROJECTIONS

For the purposes of the trade-off analysis, some reasonable drag estimate must be made for the proposed hybrid vehicle. The three basic elements of the total vehicle drag which will be considered are the aerodynamic drag, tire hystereses losses, and the tire rolling resistance and chassis losses.

A Aerodynamic Drag.

Vehicle frontal area and drag coefficient must both be established in order to determine the total aerodynamic drag.

The frontal area is really a function of the seating package selected. Utilizing the 1979 Chevrolet Malibu seating arrangement, a frontal area of 21 square feet is a resonable estimate.

As demonstrated by the full sized wind tunnel tests of the GE Centennial 100 vehicle, it is apparent that a drag coefficient of the order of .33 is possible. This value must be tempered by two factors. First, the fact that the hybrid vehicle will require some heat exchanger for its internal combustion engine will increase the drag by approximately 6% to .35. Second, the aerodynamic performance of the vehicle in yaw must be considered since the vehicle will never operate in a zero wind condition. Making the assumption that a 10 mph wind is typical, and that the average speed of the vehicle is about 40 miles per hour, a yaw angle range of ± 15° would seem reasonable.

During scale wind tunnel tests of the GE Centennial in December of 1975, the effect of yaw angle was determined to be an increase of 11% on the drag coefficient. For the purposes of calculation, therefore, drag coefficient of .39 should be used.

B Speed Influences on Tire Rolling Losses.

Based on data from a report entitled "Tire Rolling Loss Measurements" written by Calspan Corporation under contract to the DOT, the influence of vehicle speed on tire losses was determined to be

$$F = .00003\ WV$$

where F = Drag force - pounds
W = Weight - pounds
V = Speed - mph

C Tire Rolling Losses.

Tire rolling losses for radial ply tires in equilibrium operating condtions are known to be of the order of .011 pounds per pound at their rated load. However, the effect of warm-up is significant and can account for variations of up to 50% in tire rolling loss from "cold" to "warm" tires. Figure 1 is a plot of trip length verses rolling resistance illustrating this effect. This factor should be included in the trade-off analysis with the value selected based on the mission profile.

D Total Vehicle Drag.

Summing the effects outlined above, the expressions for the drag of the hybrid vehicle in the equilibrium condition [warm tires] can be written:

$$F = .011\ W + .00003\ WV + (.00249)(AC_d)V^2$$

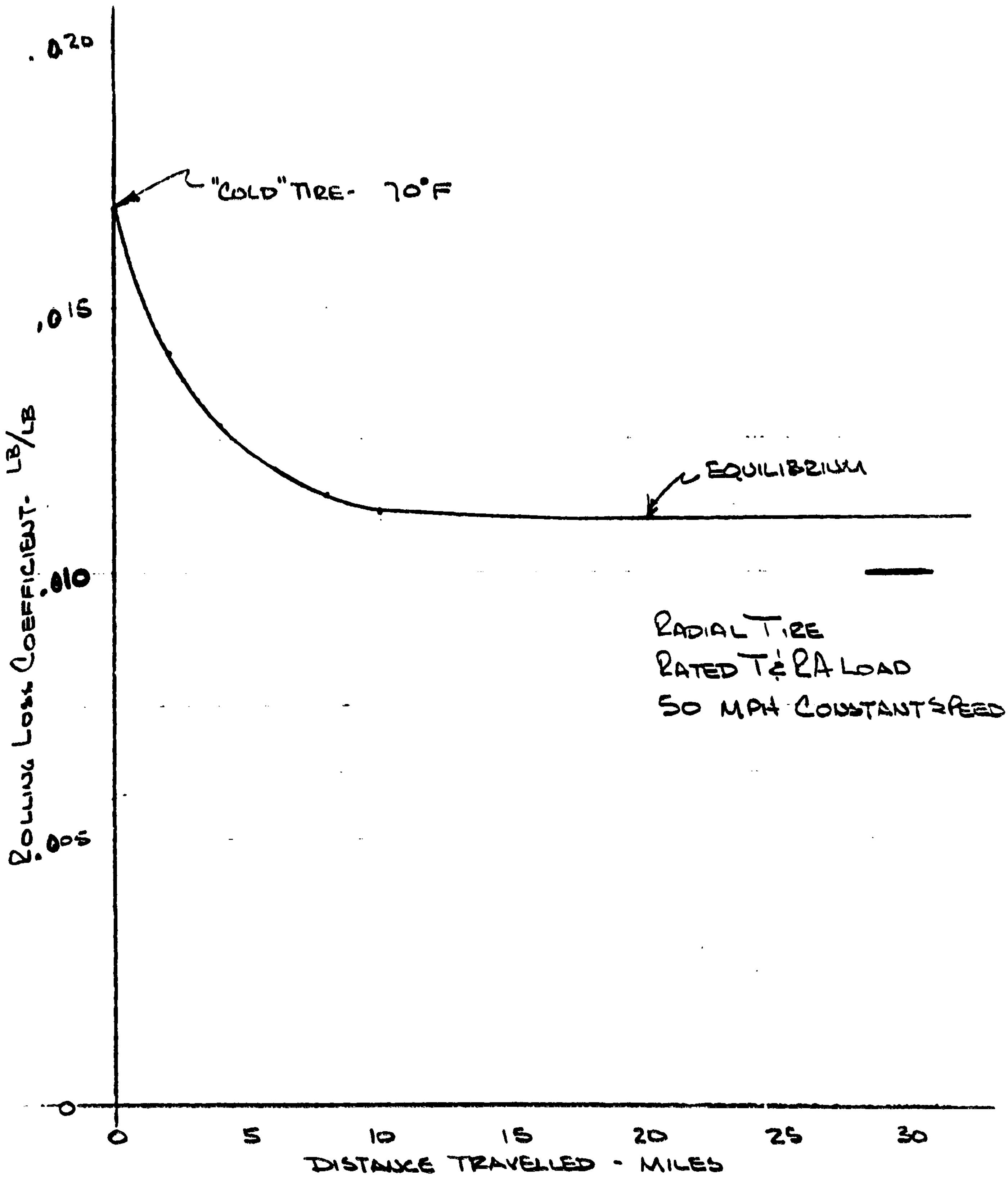
$$= .011\ W + .00003\ WV + .02\ V^2$$

where

W = vehicle wt. (pounds)
V = vehicle speed (mph)

E Effective Vehicle Weight.

The weight of the vehicle must be increased effectively for acceleration calculations to account for the rotating inertia of the wehels and tires. This amounts to approximately 70% of the wheel and tire weight. Utilizing the factors developed in section I, the weight of the vehicle must be increased by (.028)(Wg) for the purposes of acceleration calculations.



INFLUENCE OF DISTANCE TRAVELED ON TIRE DRAG

FIG 1

HEATER AND AIR CONDITIONER PERFORMANCE

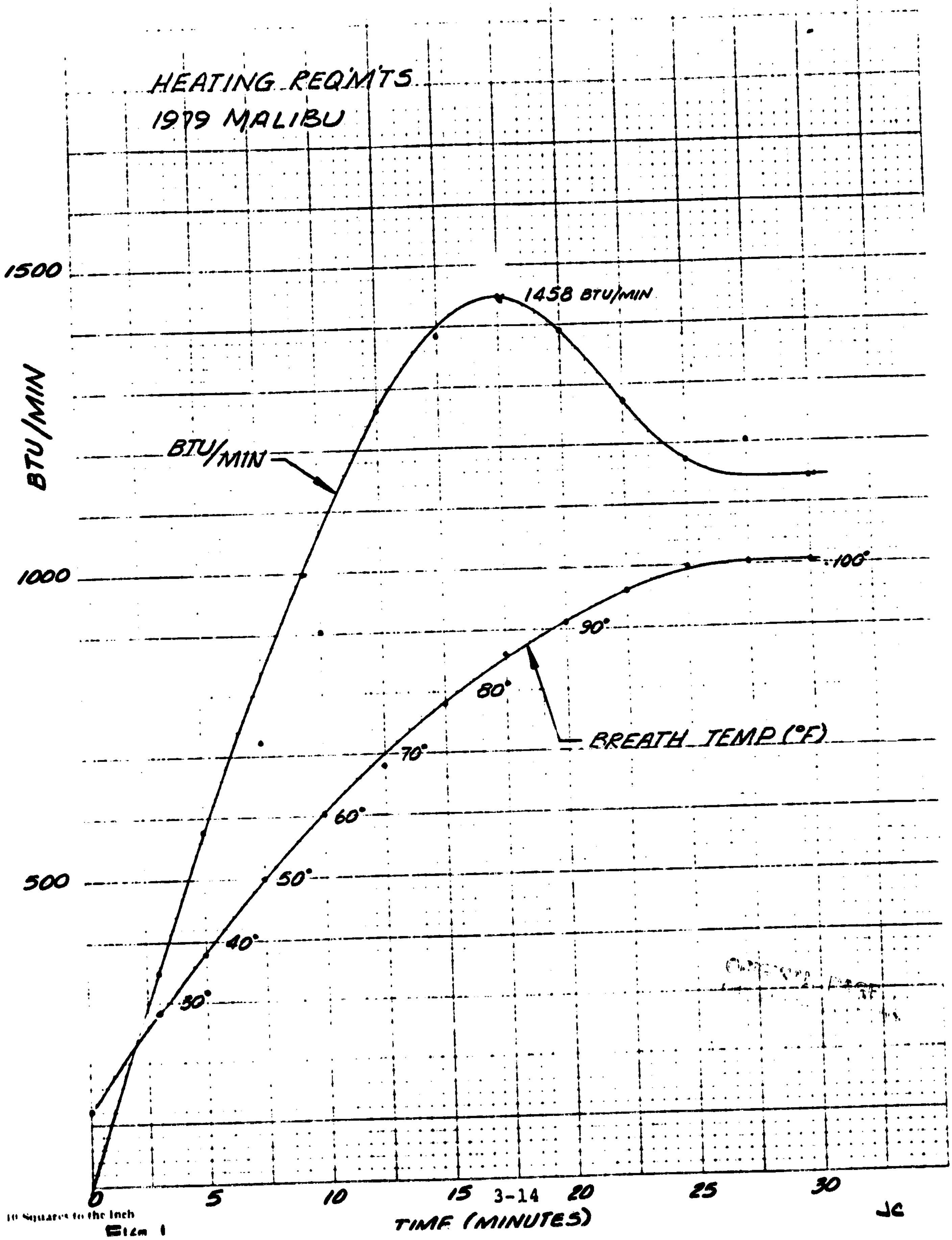
In order to provide "equivalent value" in the hybrid vehicle relative to the reference vehicle, the heater and air conditioning systems should have the same or similar performance. Tests were conducted on a 1979 Malibu 4-door sedan with 200 cubic inch 6 cylinder engine to establish these performance levels. The vehicle was instrumented with thermocouples and air flow measuring apparatus in order to measure the heat transfer to the passenger compartment.

HEATER PERFORMANCE

After an overnight soak at ambient temperatures of between 5 and 11 degrees F., the reference vehicle was started and driven at 20 mph with the heater blower on maximum. Air temperatures across the heater core and blower air flow were measured as a function of time. "Breath level" interior compartment temperatures were also monitored in order to place some measure on the vehicle warm-up time. Figure 1, illustrates the breath level temperature as a function of time, and the heat transfer to the compartment as a function of time.

AIR CONDITIONER PERFORMANCE

Similar instrumentation to the heater tests was used to measure the heat transfer from the air across the evaporator. Figure 2 illustrates the "pull down" capability of the system as a function of time after a hot soak. The engine was at idle and the vehicle not in motion. Figure 3 shows the heat transfer from the air across the evaporator for the air conditioning system while operating at its maximum capacity.



10 Squares to the Inch

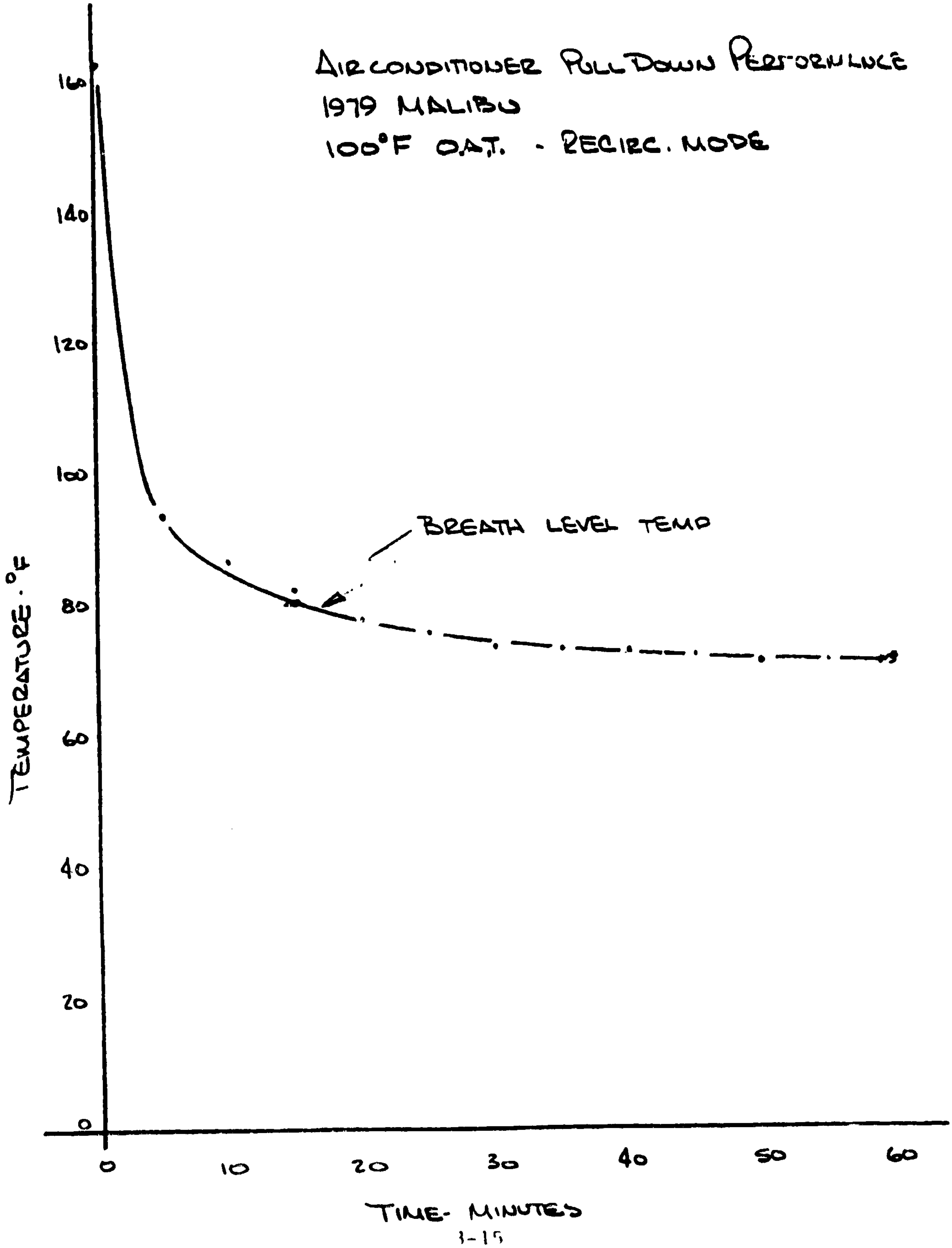

AIRCONDITIONER PULL DOWN PERFORMANCE
1979 MALIBU
100°F O.A.T. - RECIRC. MODE
BREATH LEVEL TEMP
TEMPERATURE - °F
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
TIME - MINUTES

FIG 2

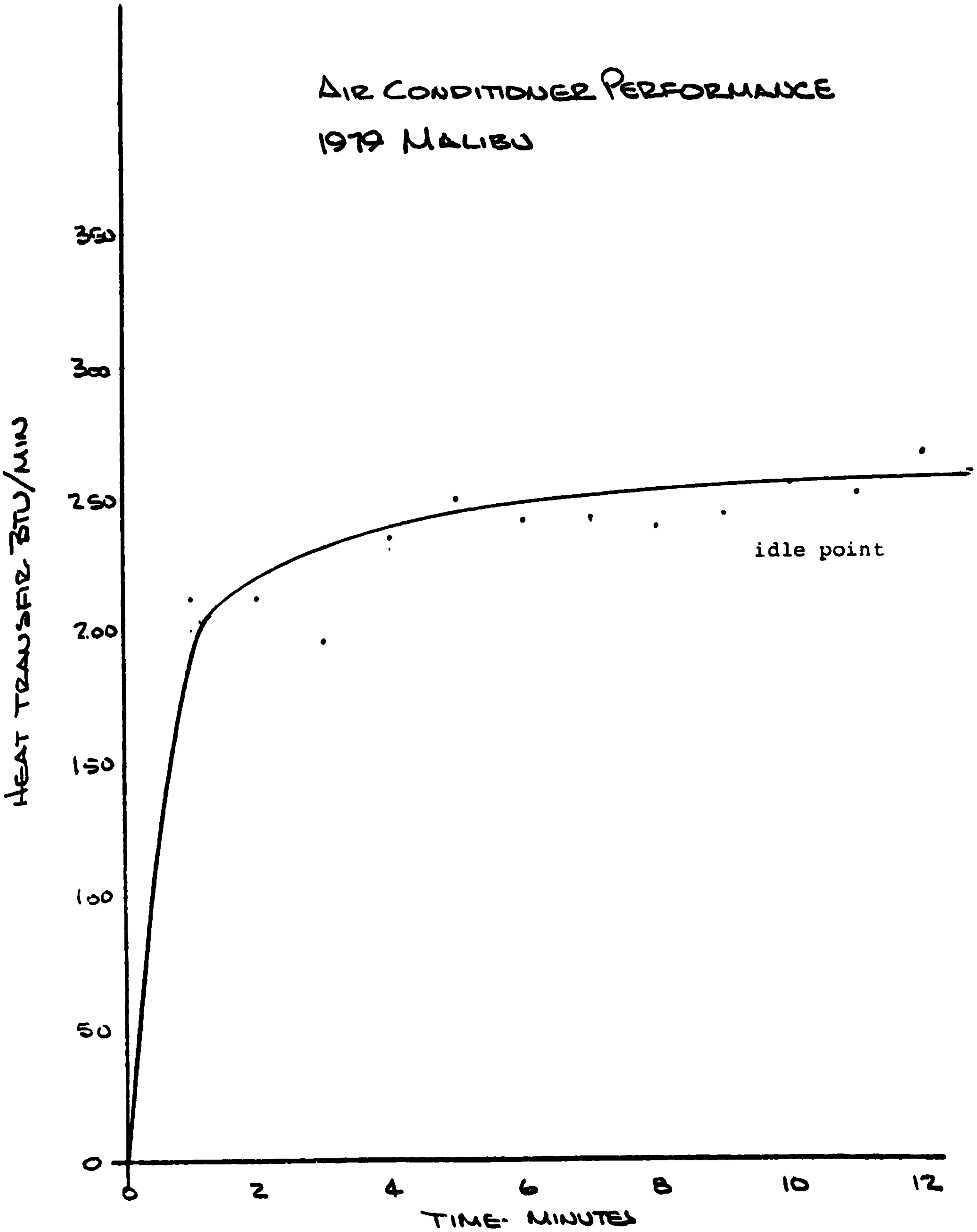


FIG 3

1-17-79
IND

A/C TEMPERATURE DROP 1-17-79

Time (Min.)	Thermocouple Lead (°F)				Inches		
	1	2	3	6	Pitot Tube	Static Tube	Diff.
Start	67	66	67	71	3.74	3.74	0
1	70	61	45	58	4.64	2.85	1.79
2	71	60	45	55	4.64	2.85	1.79
3	70	58	44	54	4.62	2.88	1.74
4	70	57	39	52	4.62	2.92	1.70
5	70	57	38	52	4.62	2.92	1.70
6	71	56	38	51	4.62	2.92	1.70
7	70	56	37	50	4.60	2.94	1.66
8	70	55	37	49	4.58	2.96	1.62
9	71	55	36	49	4.58	2.95	1.63
10	70	55	35	48	4.58	2.97	1.61
11	70	55	36	48	4.59	2.98	1.61
12	71	55	34	48	4.58	2.98	1.60
13	69	55	38	48	4.58	2.98	1.60
14	73	55	39	48	4.58	2.98	1.60
15	72	54	38	48	4.58	2.98	1.60

Thermocouple Lead	Location
1	Outside Air
2	Air to A/C Core
3	Air From A/C Core
6	Passenger Compt. Breath

HEATING TEMPERATURE RISE 1-17-79

Time (Min.)	Thermocouple Lead (°F)						Inches		
	1	2	3	4	5	6	Pitot Tube	Static Tube	Diff.
Start	12	24	11	13	12	11	3.43	3.43	0
3	13	28	18	52	73	18	3.80	3.14	.66
5	13	38	25	78	99	30	3.84	3.11	.73
7 1/2	11	50	42	107	130	56	3.86	3.07	.79
10	13	60	49	129	154	85	3.90	3.04	.86
12 1/2	10	68	42	146	172	106	3.95	2.98	.97
15	12	78	50	159	187	121	4.00	2.92	1.08
17 1/2	12	86	53	167	193	170*	4.01	2.91	1.10
20	13	91	58	166	192	184	4.02	2.89	1.13
22 1/2	12	96	68	167	192	188	4.03	2.88	1.15
25	14	100	76	167	192	182	4.04	2.87	1.17
27 1/2	12	103	76	168	193	185	4.05	2.85	1.20
30	12	106	80	167	192	186	4.06	2.84	1.22

Thermocouple Lead	Location
1	Outside Air
2	Passenger Compt. Breath
3	Air to Heater Core
4	Air from Heater Core
5	Heater Core Water Temp.
6	Radiator Water Temp.

*Rise is Rapid

ACCESSORY POWER REQUIREMENTS

Accessory power requirements for the hybrid vehicle were derived from measurements on the reference vehicle. Power requirements for the air conditioner, the alternator, and the power steering pump were determined by measurements made on a Chevrolet Malibu using a strain gauged crankshaft pulley. The results of these tests follow.

A Air Conditioner Power Requirements. (Drive Ratio* 1.4:1)

Figure 1 is a plot of compressor horsepower as a function of compressor speed. The compressor is operating at its maximum load. The ratio of compressor speed to vehicle speed is 50.4 rpm/mph.

B Alternator Power Requirements. (Drive Ratio 3.1:1)

Figure 2 is a plot of alternator power requirements as a function of speed and charging current. The ratio of alternator speed to car speed is 111.6 rpm/mph.

C Power Steering Power Requirements. (Drive Ratio 1.2:1)

Figure 3 is a plot of road load power steering pump requirements with zero steering effort applied. In addition to these losses, which are essentially parasitic, there is an additional requirement for parking and high speed maneuvers. Figure 3 also presents the instantaneous power required by the power steering pump for maximum performance.

Although these power levels are high, they represent instantaneous values. Tests run on simulated city and highway driving cycles yield more realistic power steering system power requirements for the purposes of range calculations.

Losses on the city driving cycle are approximately .75 horsepower while the highway driving cycle will drop these values to about .65 horsepower on the average.

*Ratio to engine speed

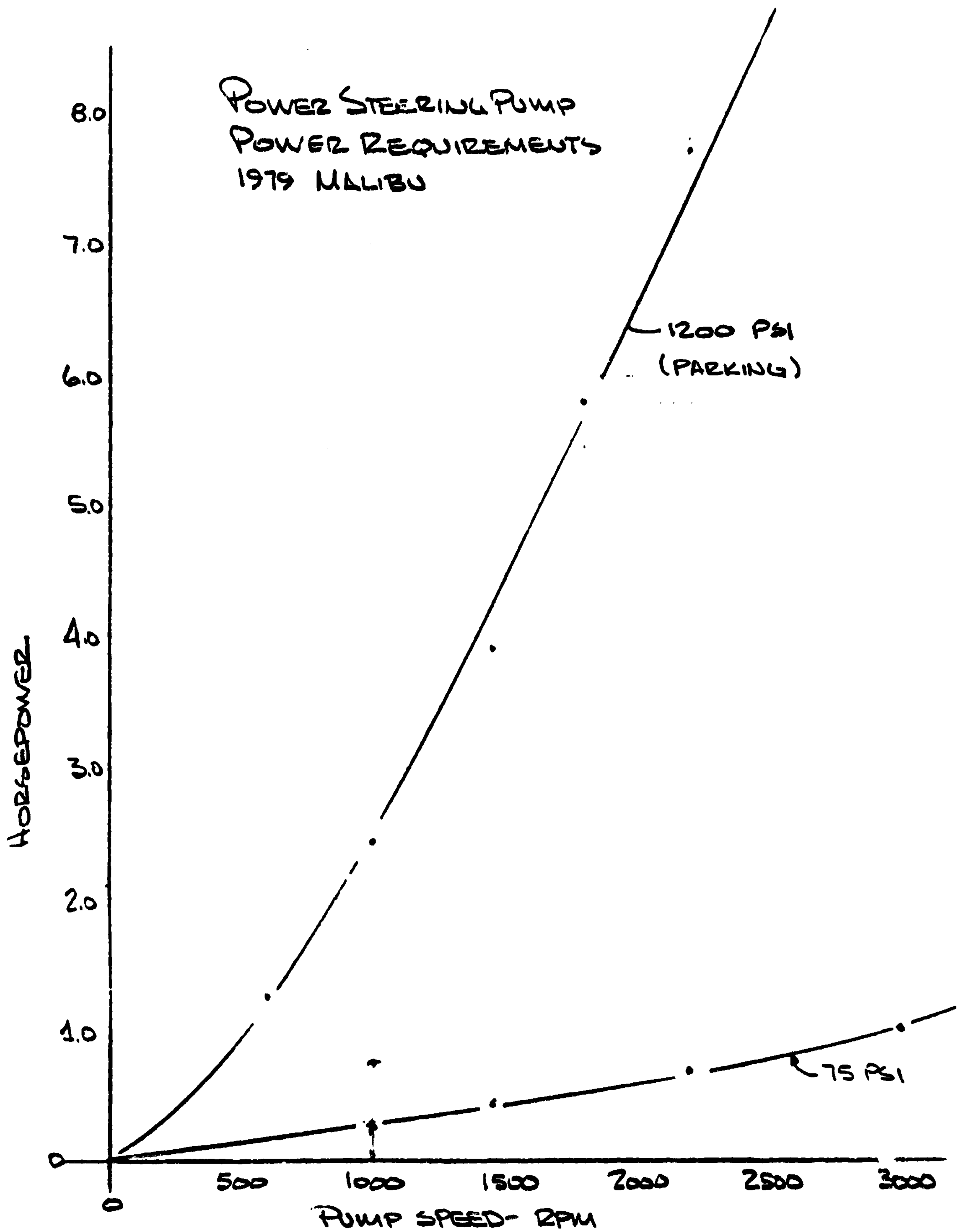


FIG 3

1-17-79
MAP

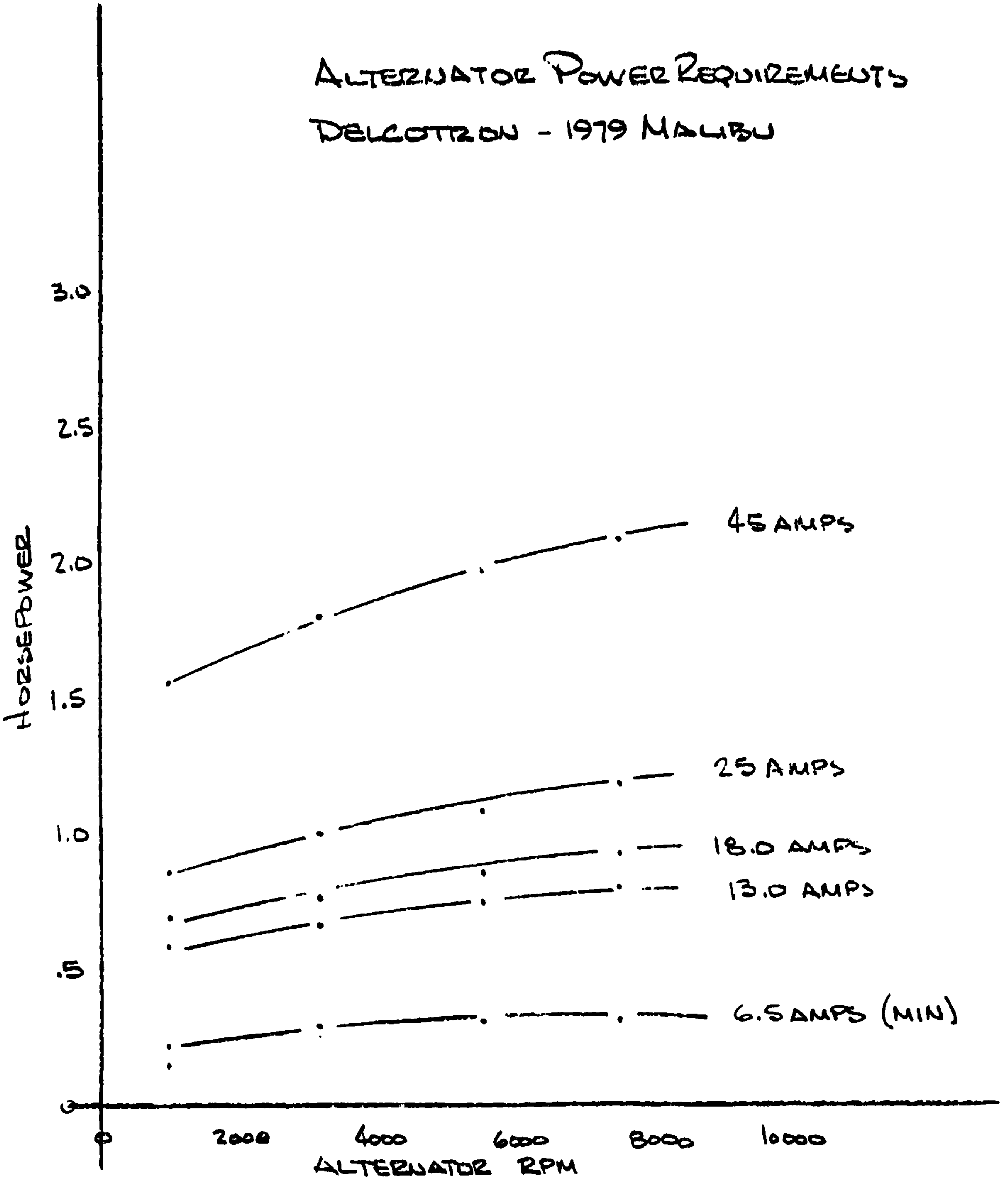


FIG 2

1-15-79
MAP

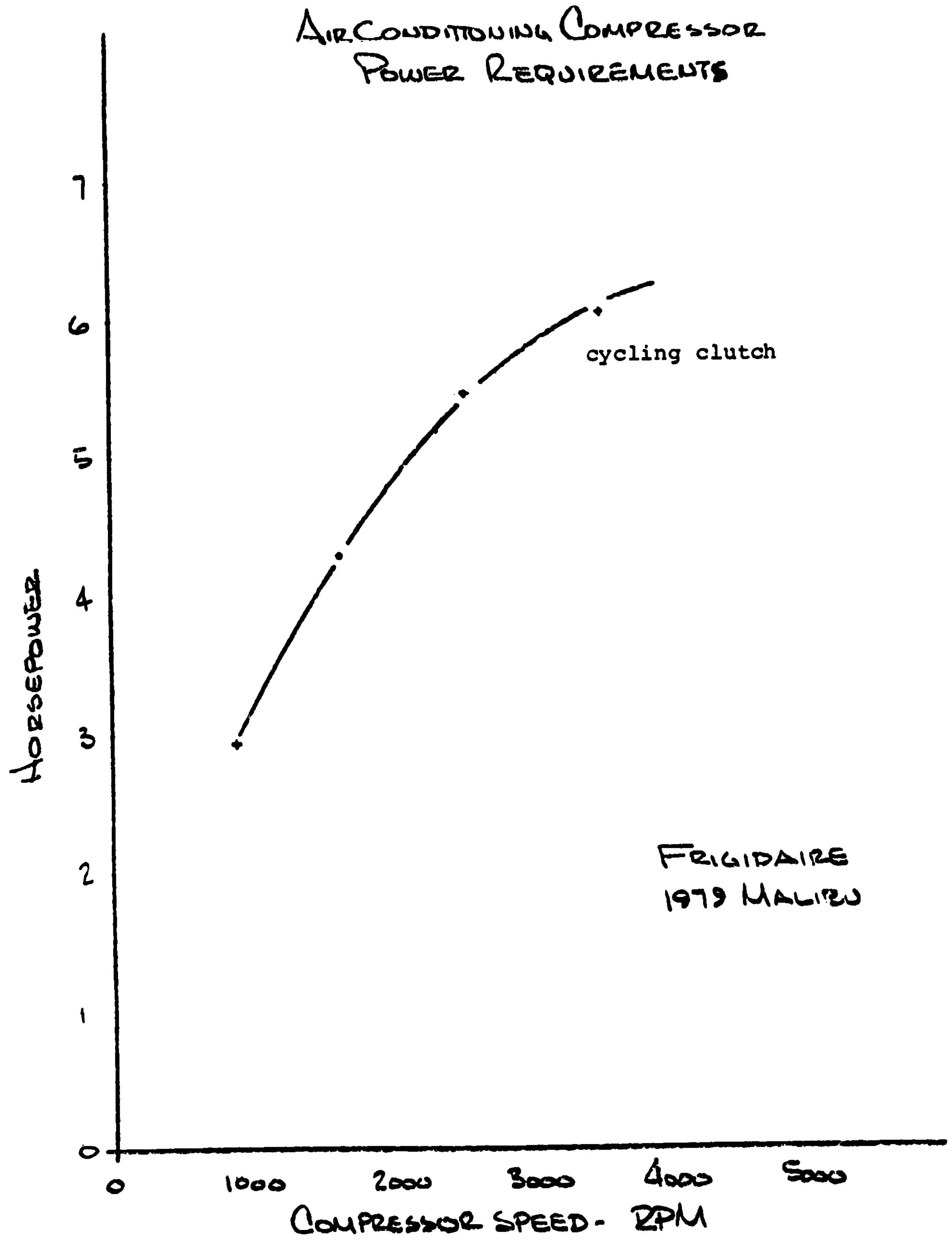


Fig 1

1-15-79
MAP

TRIAD SERVICES INC. • 32049 HOWARD ST. • MADISON HEIGHTS, MICH. 48071 • 313/589-2355

February 6, 1979

Dr. A. F. Burke
General Electric Company
Corporate Research and Development
Building 37 - Room 2078
P.O. Box 43
Schenectady, New York 12301

Dear Andy:

The following chart summarizes the results of the accessory power system tests run on a 1979 Malibu vehicle.

Accessory	Power Requirements (Watts)
Parking Lights	101
Low Beam Headlights	203
High Beam Headlights	254
Turn Signals (avg.)	84
Hazard Lights (avg.)	179
Interior Lights	45
Windshield Wipers	
dry - low speed	98
wet - low speed	90
dry - high speed	83
wet - high speed	70
Ventilation Fan	
low speed	32
2nd speed	73
3rd speed	112
high speed	159
Rear Window De-fogger	231
Radio	10
Cigarette Lighter	62
Horn	25
Engine Ignition System	25
Air Conditioner Clutch	44

The regulated charging system voltage on a charged battery was 14.6 volts D.C.

We are continuing with our preliminary packaging studies. I hope to have some drawings available when I see you on the 21st.

Very truly yours,

Michael A. Pocobello

MAP/np

cc: R. H. Guess

WEIGHT ANALYSIS FOR TRADE-OFF STUDIES

ASSUMPTIONS

- 4 DOOR SEDAN
- 1979 MALIBU SEATING PACKAGE
- POWER STEERING STANDARD
- POWER BRAKES STANDARD
- AIR CONDITIONING STANDARD

WEIGHT RELATIONSHIP

$$W_G = \frac{.856 - \sqrt{.733 - (21.2 \times 10^{-5})K1}}{10.6 \times 10^{-5}}$$

WHERE

$K1 = K + 1.18D + 23.2P + 1.4L + 1.53F$

AND

K = 1017 + LUGGAGE + PASSENGER LOAD + MAX. FUEL LOAD + BATTERY LOAD + MOTOR WEIGHT + CONTROL WEIGHT

D = ENGINE DISPLACEMENT (CU.IN.)

P = NUMBER OF PASSENGERS

L = WHEELBASE (INCHES)

F = FUEL CAPACITY (GALLONS)

TOTAL VEHICLE DRAG

$$F = .011\,W + .00003\,WV + .02V^2$$

WHERE W = TEST WEIGHT (POUNDS)

V = VEHICLE SPEED (MPH)

ASSUMPTIONS

- 1979 MALIBU FRONTAL AREA (21 FT^2)
- YAW WEIGHTED DRAG COEFFICIENT OF .39
- "WARM" RADIAL PLY TIRES

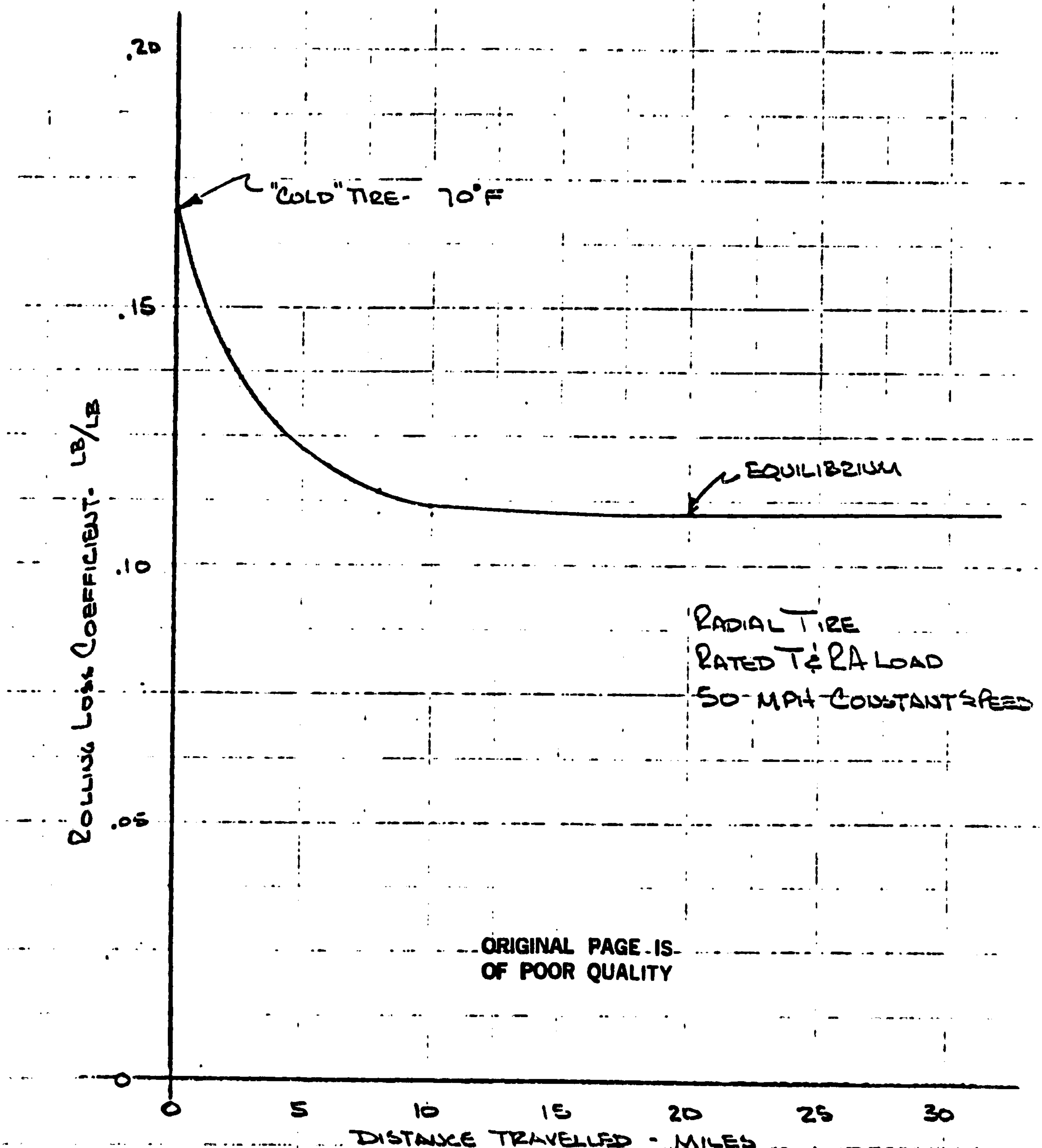


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FIG. 1 INFLUENCE OF DISTANCE TRAVELED ON TIRE DRAG

AUXILIARY POWER REQUIREMENTS

Accessory	Power Requirements (Watts)
Parking Lights	101
Low Beam Headlights	203
High Beam Headlights	254
Turn Signals (avg.)	84
Hazard Lights (avg.)	179
Interior Lights	45
Windshield Wipers	
dry - low speed	98
wet - low speed	90
dry - high speed	83
wet - high speed	70
Ventilation Fan	
low speed	32
2nd speed	73
3rd speed	112
high speed	159
Rear Window De-fogger	231
Radio	10
Cigarette Lighter	62
Horn	25
Engine Ignition System	25
Air Conditioner Clutch	44

ACCESSORY POWER SYSTEMS

SYSTEMS

- POWER STEERING
- POWER BRAKES
- AIR CONDITIONER
- LIGHTING
- HEATER & DEFROSTER
- WINDSHIELD WIPING
- TRANSMISSION CLUTCHING
- COMFORT & CONVENIENCE ITEMS

CONVENTIONAL ACCESSORY POWER SYSTEMS

SYSTEM	POWER SOURCE
POWER STEERING	OPEN CENTERED HYDRAULIC
POWER BRAKES	ENGINE MANIFOLD VACUUM BOOSTED
AIR CONDITIONER	VAPOR-COMPRESSION-ENGINE DRIVEN
LIGHTING	ALTERNATOR (14.6V)
HEATER & DEFROSTING	WASTE HEAT AND ALTERNATOR
WINDSHIELD WIPING	ALTERNATOR
TRANSMISSION CLUTCHING	OPEN CENTERED HYDRAULIC
COMFORT & CONVENIENCE	ALTERNATOR
ENGINE STARTING	ACCESSORY BATTERY

HEATER/DEFROSTER

- Waste Engine and Motor Heat
- Auxiliary Burner
- Stored Heat (Moulten Salt?)
- Heat Pump Augmented by Waste Heat

POWER BRAKE SYSTEMS

- Open-Center Hydraulic Booster
- Closed-Center Hydraulically Boosted with Charging Valve
- Closed-Center Hydraulically Boosted with Variable Displacement Pump
- Manual Drum Brakes/Regen to Zero Speed

POWER STEERING SYSTEMS

- Open-Centered Hydraulic System
- Closed-Center Hydraulic System with Charging Valve
- Closed-Center Hydraulic System with Variable Displacement Pump

ACCESSORY ELECTRICAL SYSTEMS

- Separate Alternator Driven from Prime Movers
- Alternator Integral with Drive Motor
- DC/DC Converter
- High Voltage Accessories - Powered from Main Battery Pack

TRANSMISSION CLUTCHING

OPEN CENTERED HYDRAULIC

- DRIVELINE INTEGRAL
- ACCESSORY PACKAGE

CLOSED-CENTER HYDRAULIC

ELECTRO-MAGNETIC

ENGINE STARTING SYSTEMS

- Low Voltage System/Small Motor/ Crude Gearset. Intended for Infrequent Use.
- High Voltage System/Lubricated Gearset/ High Motor Rating for Frequent Use
- Drive Motor Starts Engine through Drive-Line (vehicle must be in motion)
- Drive Motor Starts Engine Independent of Vehicle Drive

POSSIBLE SYSTEM ALTERNATES

- HEAT ENGINE IDLING
    - ACCESSORIES DRIVEN BY HEAT ENGINE
    - HEATER AND A/C CONVENTIONAL
    - ENGINE STARTING CONVENTIONAL
    - ACCELERATION RESPONSE BETTER
- ELECTRIC MOTOR IDLING
    - NO ARMATURE ELECTRONICS
    - OVER-RUNNING CLUTCH ACCESSORY DRIVE
    - DRIVE MOTOR STARTS ENGINE
    - HEATER ?
- NEITHER PRIME MOVER IDLING
    - SEPARATE ACCESSORY DRIVE MOTOR?
    - SEPARATE ENGINE STARTING MOTOR?
    - HEATER AND AC?
    - STORAGE FOR POWER STEERING AND TRANSMISSION SHIFTING
    - ACCESSORY POWER SOURCE?

PACKAGING CONSIDERATIONS - MAJOR SYSTEMS

(1) SEATING PACKAGE - 1979 MALIBU - 4 DOOR

(2) ENGINE - 4 CYL (70-80 HP)

(3) LEAD ACID BATTERIES (700 POUNDS)

(4) ELECTRIC MOTOR - (GE 2364)

(5) 4 SPEED AUTOMATIC TRANSMISSION

(6) 12 GALLON FUEL TANK

(7) PARALLEL HYBRID WITH DIFFERENTIAL DRIVELINE INPUT

(8) CATALYTIC CONVERTER FOR EMISSION CONTROL

BASIC INTERIOR DIMENSIONS-REFERENCE VEHICLE

Front Compartment

		DEGREES	IN	MM
W20	Centerline Occupant to Centerline Car		14.48	368
H61	Effective Headroom		38.70	983
L64	Maximum Effective Leg Room		42.75	1086
H30	H Point to Heel Hard (chair height)		8.97	228
L40	Back Angle	26.5		
L42	Hip Angle	99.5		
L44	Knee Angle	131.0		
L46	Foot Angle	87.0		
L53	H Point to Heel Point		35.07	891
L17	H Point Travel		6.73	171
H58	H Point Rise		.98	25
W3	Shoulder Room		51.32	1456
W5	Hip Room		52.20	1326
W16	Seat Width		49.49	1257

Rear Compartment

		DEGREES	IN	MM
L50	H Point Couple		32.56	827
W25	Centerline Occupant to Centerline Car		13.27	337
H63	Effective Head Room		37.68	957
L51	Maximum Effective Leg Room		38.00	965
H31	H Point to Heel Point (chair height)		11.73	298
L41	Back Angle	27		
L43	Hip Angle	92		
L45	Knee Angle	102		
L47	Foot Angle	118.5		
W4	Shoulder Room		57.08	1450
W6	Hip Room		55.59	1412

Control Location

		DEGREES	IN	MM
H18	Steering Wheel Angle	19.5		
L7	Steering Wheel Torso Clearance		13.38	340
L13	Brake Pedal Knee Clear		24.42	595
L52	Brake Pedal to Accelerator		4.48	114

CRITERION FOR SELECTION OF PACKAGE

(1) CRASHWORTHINESS
- STRUCTURAL REQUIREMENTS
- DYNAMICS
- FUEL SYSTEM PROTECTION

(2) VEHICLE MASS

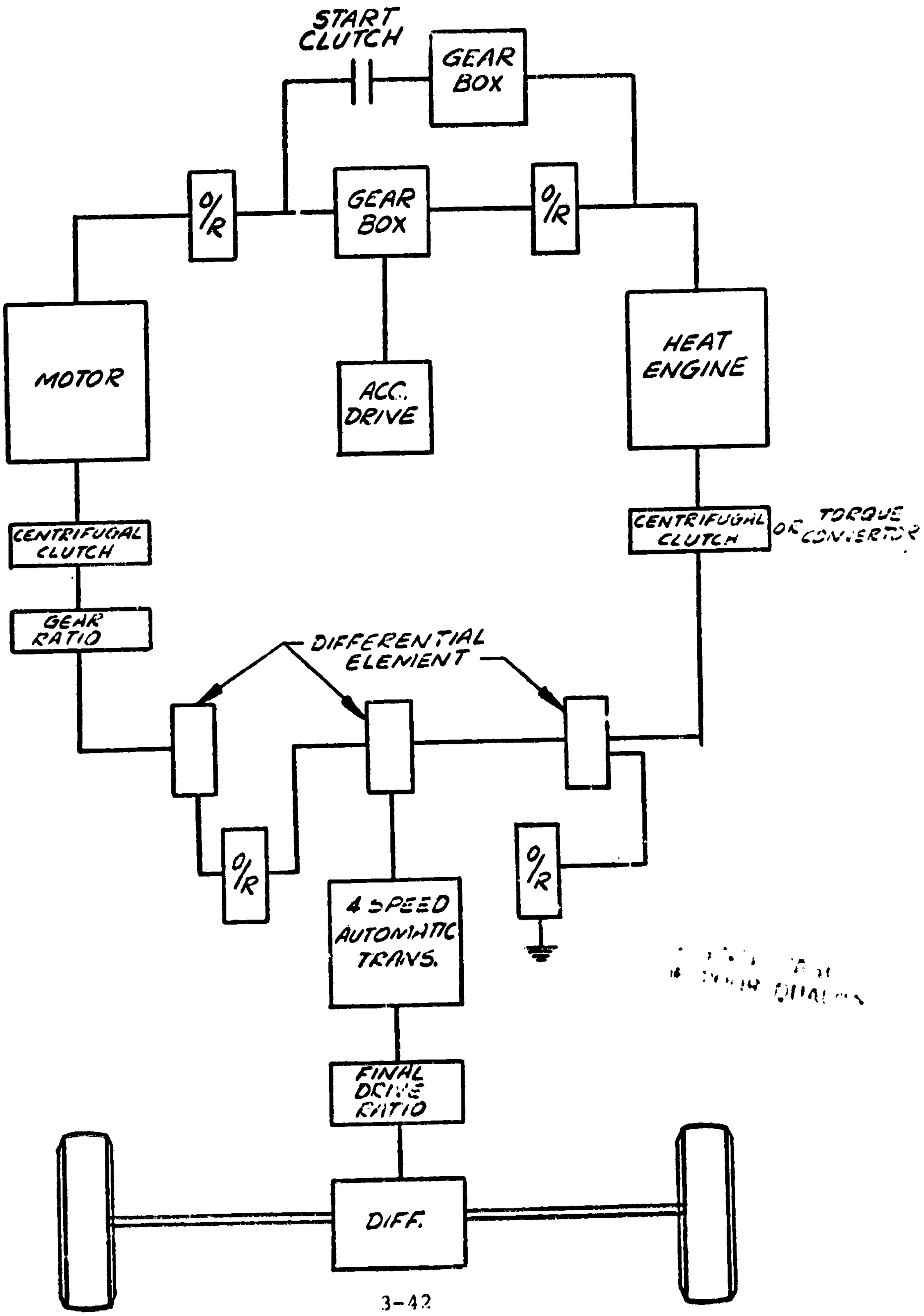
(3) HANDLING CHARACTER
- WEIGHT DISTRIBUTION
- POLAR MOMENT OF INERTIA
- SUSPENSION TYPES

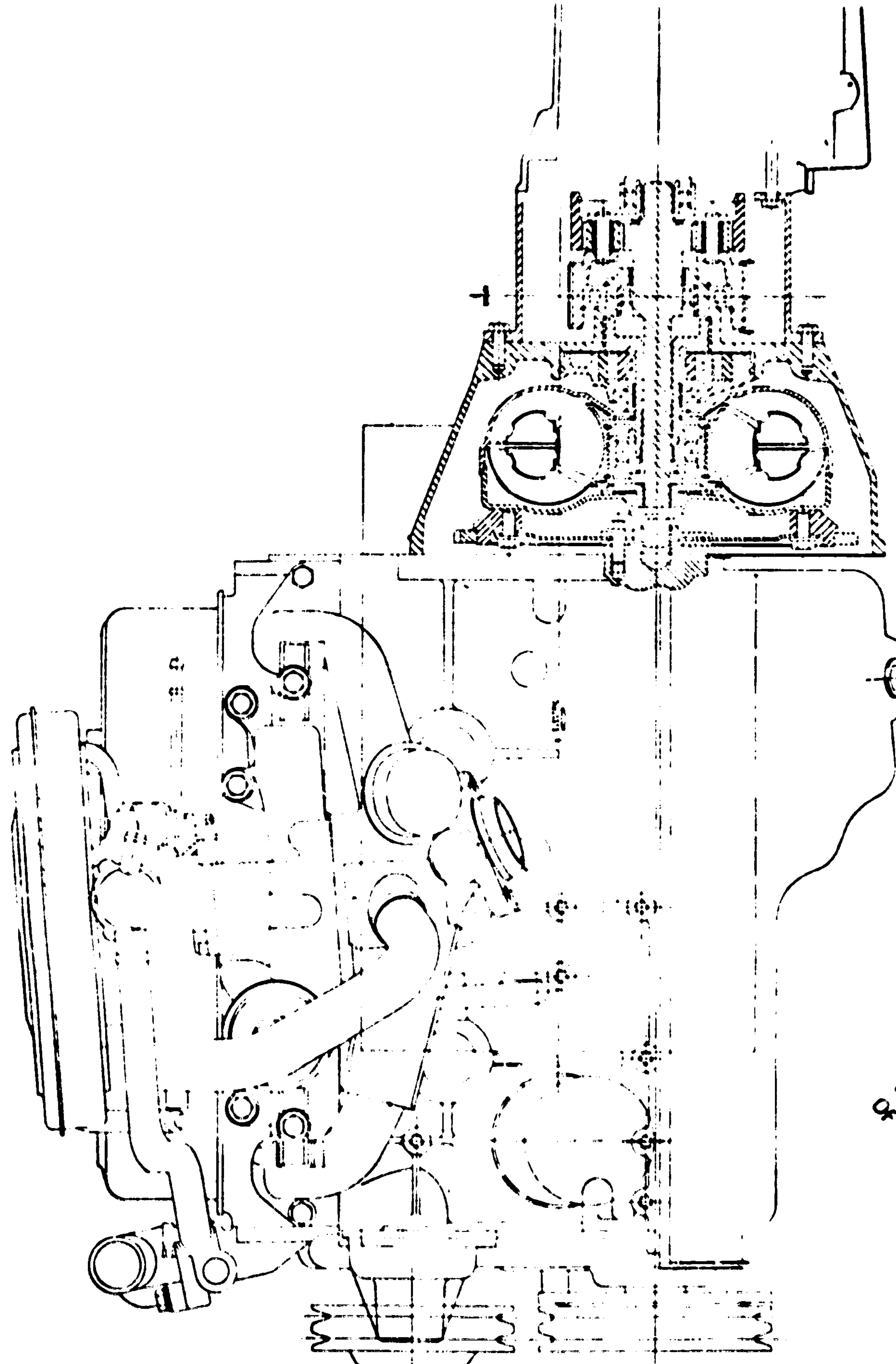
(4) SERVICEABILITY
- ENGINE
- CONTROL SYSTEM
- BATTERY

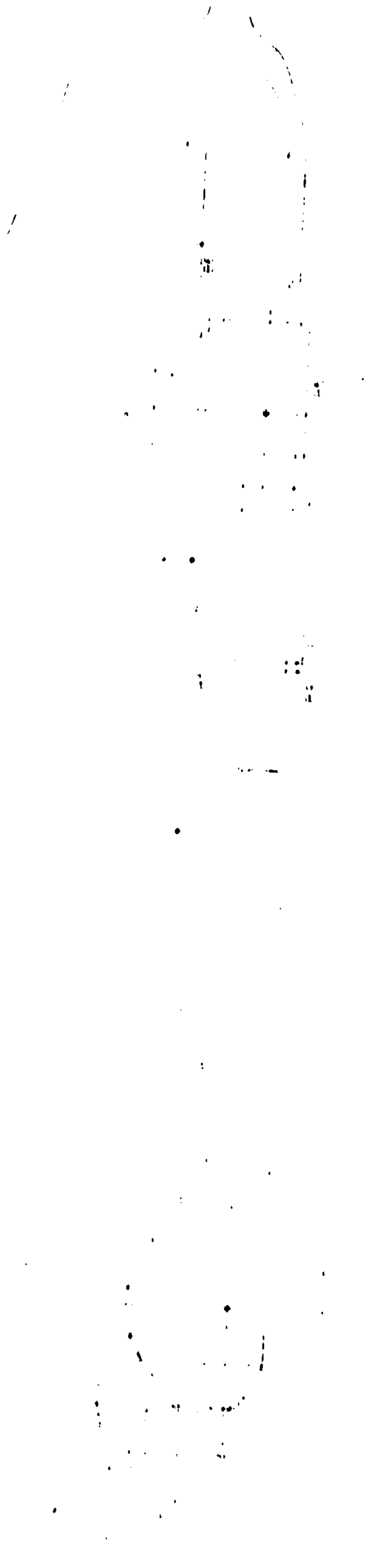
(5) LUGGAGE COMPARTMENT
- SIZE
- LOCATION

(6) PASSENGER COMPARTMENT INTRUSION

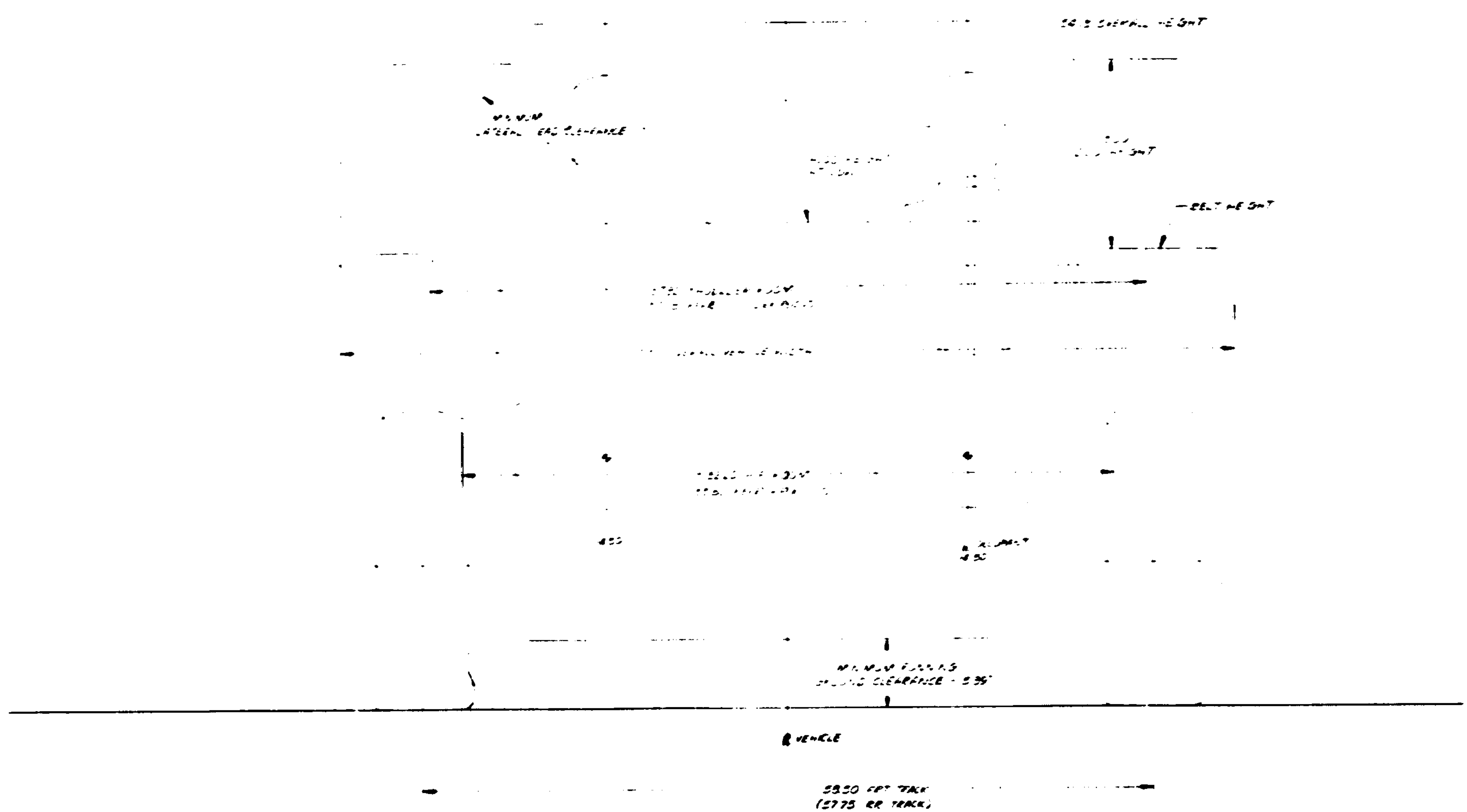
MECHANICAL COMPONENT PACKAGING SCHEMATIC



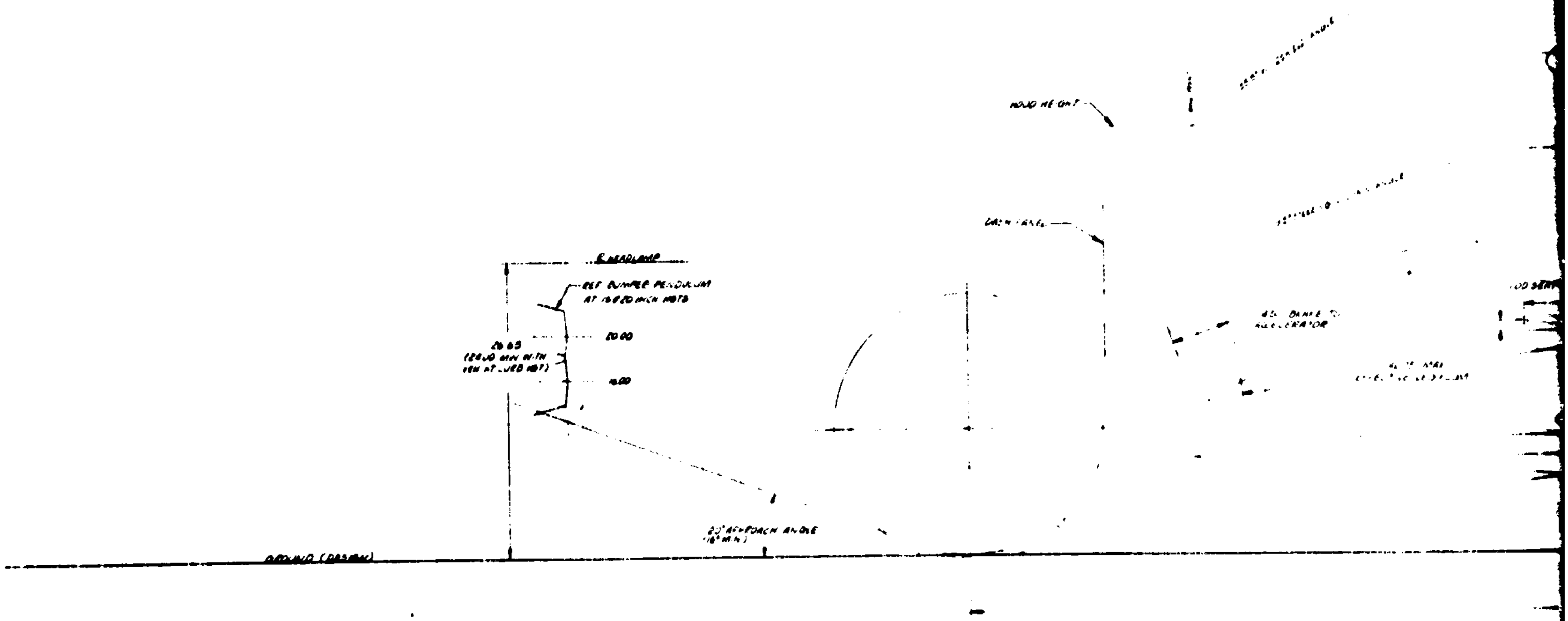




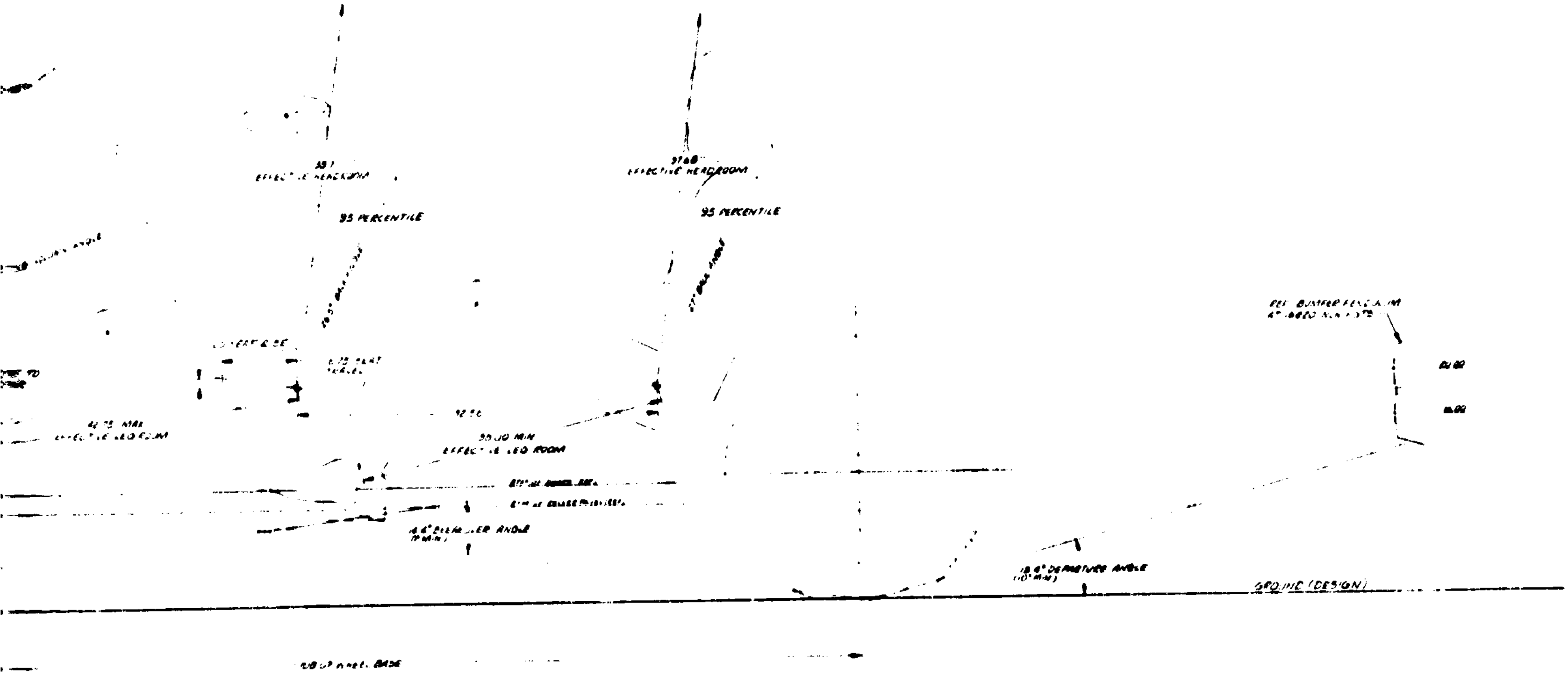
Packaging Composite



Preliminary Layout - Space Relation

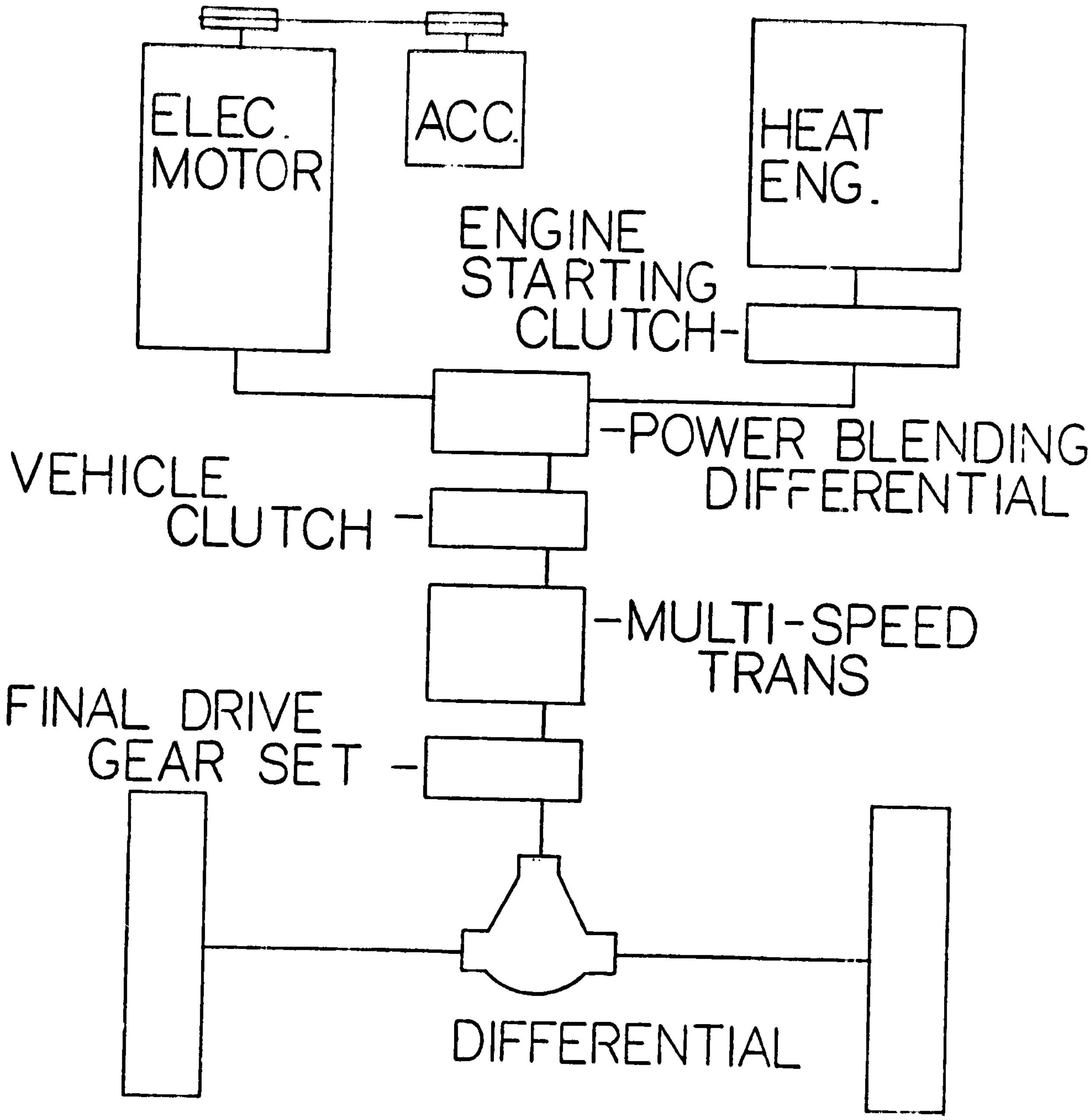


Preliminary Layout -

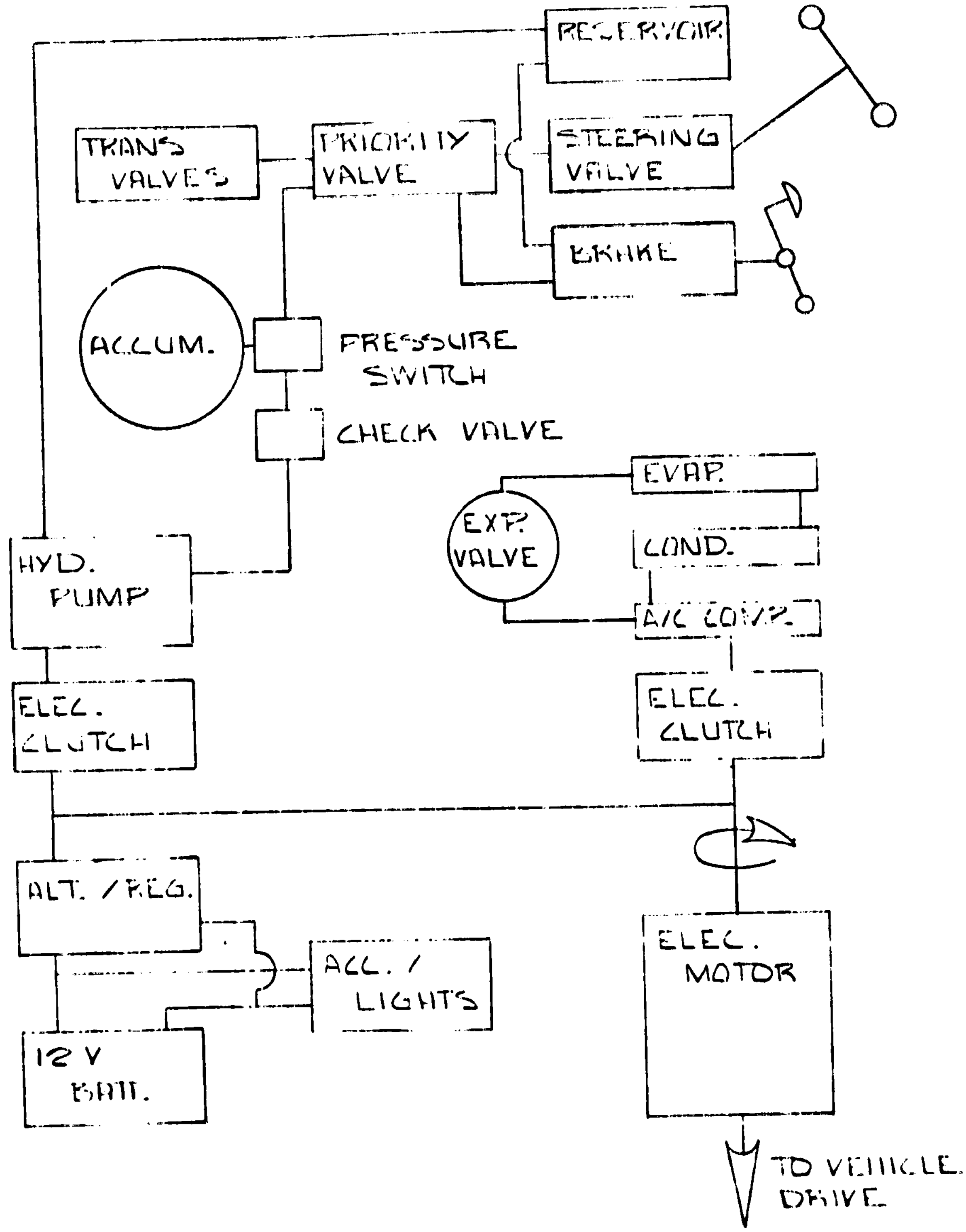


ːnary Layout - Space Relation

FOLDOUT FRAME



SCHEMATIC
DRIVE ARRANGEMENT



BLOCK DIAGRAM
ACCESSORY SYST.

Section 4

MOTORS AND CONTROLS FOR HYBRID VEHICLES

Section 4

MOTORS AND CONTROLS FOR HYBRID VEHICLES

4.1 BACKGROUND

In 1975, General Electric Corporate Research and Development began a long-range program to make substantial improvements in motors and controls for electric and hybrid vehicles.

Initially, a comprehensive survey was made considering all types of motors and controls which were amenable to electric and hybrid vehicles depending upon the time frame in which they were used. This survey was presented orally to the Department of Energy (then called Research and Development Administration) as part of a comprehensive plan to develop advanced electric vehicles (see Attachment A). The General Electric Company, Electric Storage Battery Inc., and Triad Services Inc., recommended the overall program and offered to submit an unsolicited proposal. This offer was declined, and the proposal was never formalized. The survey of motors and controls was not published, but the draft version has been used heavily by General Electric in program definition, proposed preparation, and reports in this, as well as a number of other subsequent projects.

Several major developments either planned, under way, or completed which followed this comprehensive design are:

1. Development of an electric vehicle designed from the ground up to demonstrate the state-of-the-technology drive system and to establish a baseline against which to identify and measure improvements.[1] This was actually built with a commercially available General Electric direct current series motor and SCR chopper direct current armature control and is identified as the GE-100 Centennial Electric (see Attachment B).
2. Development of an inductor motor/alternator with flywheel and load inverter for acceleration and regenerative braking for the Department of Energy.[2]
3. Development of a Department of Energy Near-Term Electric Vehicle with improved performance and utilizing regeneration advancements in the state-of-the-technology in the separately excited direct current motor (Figure 4-1), the regenerative armature chopper utilizing new transistorized power modules, microcomputer controls, and on the improved lead-acid battery.[3]
4. Development of a high-speed induction motor being built for National Aeronautics and Space Agency (NASA) Lewis Research Center featuring low volume, low weight, and low cost.[4] This development is aimed at electric vehicles

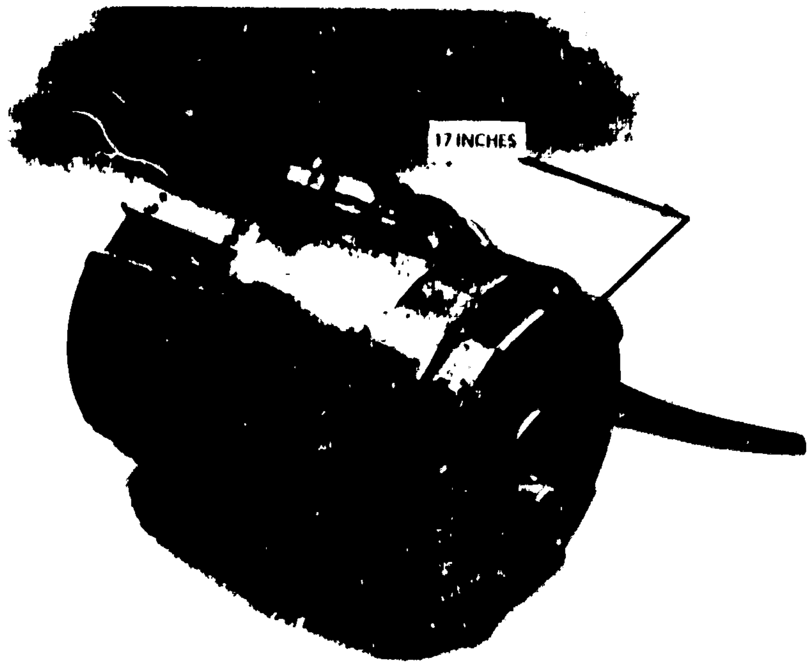


Figure 4-1. Direct Current Separately Excited Motor Used in Near-Term Electric Vehicle

that will succeed the Near-Term Vehicles perhaps in the mid 1980's. A proof-of-concept motor is shown in Figure 4-3, which compares it to the equivalent direct current separately excited motor developed in Item 3.

5. Development of an advanced permanent magnet disc motor on a General Electric program intended to produce very lightweight, low volume, and very low-cost electric drives. This work is aimed at the truly advanced electric vehicle in the latter part of the 1980's and early 1990's.[5,6] A proof-of-concept motor has been developed and is shown in Figure 4-2 which compares it to the equivalent direct current separately excited motor developed in Item 3.

Each of the items listed above was accomplished after extensive modeling and analysis. These studies were consulted extensively in the sections that follow to make the required design trade-off studies for the hybrid vehicle program.

4.1.1 PREVIOUS TRADE-OFF STUDIES

The overall drive system requirements and the detailed evaluation of alternate direct current drives were made for the Near-Term Electric Vehicle Program, Phases I and II. These will not be repeated in this study. Specific designs and ratings will be scaled to accomplish the trade-off using direct current drives for the hybrid vehicle.

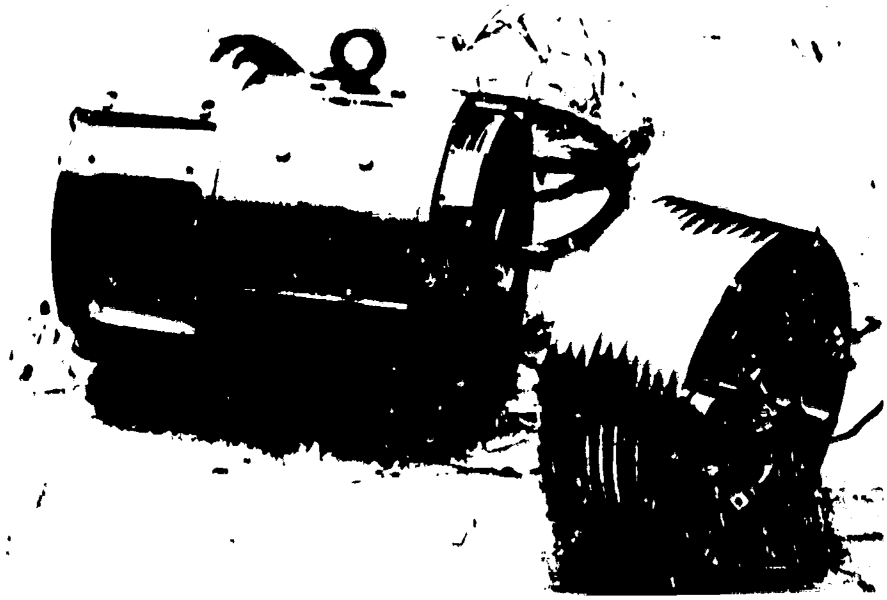


Figure 4-2. Comparison of PM Disc Synchronous Motor with dc Separately Excited Motor

Figure 4-3. Comparison of High-Speed Induction Motor and Gear Reducer with dc Separately Excited Motor

The alternating current drive evaluations have met the overall drive system requirements as developed in the Near-Term Electric Vehicle Program, Phases I and II. Additional studies have been undertaken and are described subsequently.

In early 1978, General Electric Corporate Research and Development conducted a trade-off study of a myriad of alternate ac drive systems to identify an appropriate drive or drives that should be undertaken by General Electric. This study was not published, but summary sheets are presented as Attachment C which reports the findings, conclusions, and recommendations. The two motor development programs mentioned earlier, the NASA high-speed ac induction motor and the longer range General Electric synchronous ac permanent magnet disc motor programs were specifically recommended and are the direct result of this study.

4.1.2 PRESENT TRADE-OFF STUDY

As part of the hybrid vehicle trade-off studies, additional work has been done to examine the application of ac drives to the hybrid vehicle. An internal memorandum was issued describing the specific information needed. The resulting information is given in Attachment D. This attachment provides the necessary scaling factors for ac motors and controls for determining size, weight, and cost.

Detailed information of reference ac and dc motors to determine dynamic performance was provided by the General Electric DC Motor and Generator and Small AC Motor Departments, respectively. These designs and this scaling methodology are given in Attachment D.

4.1.3 PRODUCIBILITY ANALYSIS

A detailed study of producibility and cost of the power conditioning unit for the Near-Term Electric Vehicle has been made and is used in the detailed trade-off studies. This is given in Attachment E.

4.2 TECHNICAL DISCUSSION

This section summarizes the trade-offs that were made during the studies noted in Section 4.1 of this volume.

The electric propulsion system chosen is one that has regeneration capability. Preliminary evaluation of the hybrid vehicle requirements indicated the drive for the Near-Term Electric Vehicle would come close to fulfilling the hybrid vehicle requirements.

Figures 4-4 and 4-5 show the alternate types of motors and controls which were considered. Initial screening results are as follows.

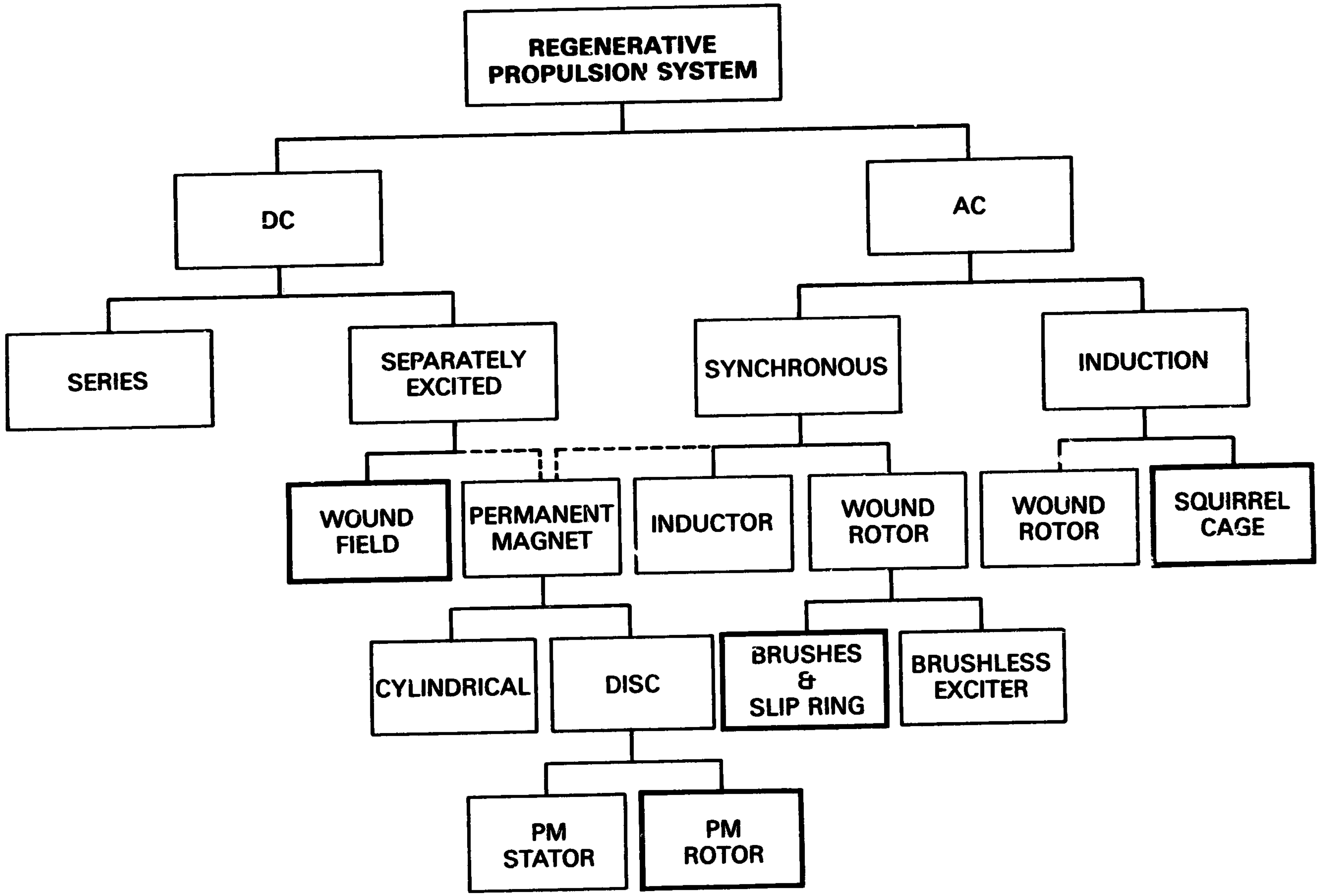


Figure 4-4. Candidate Motors

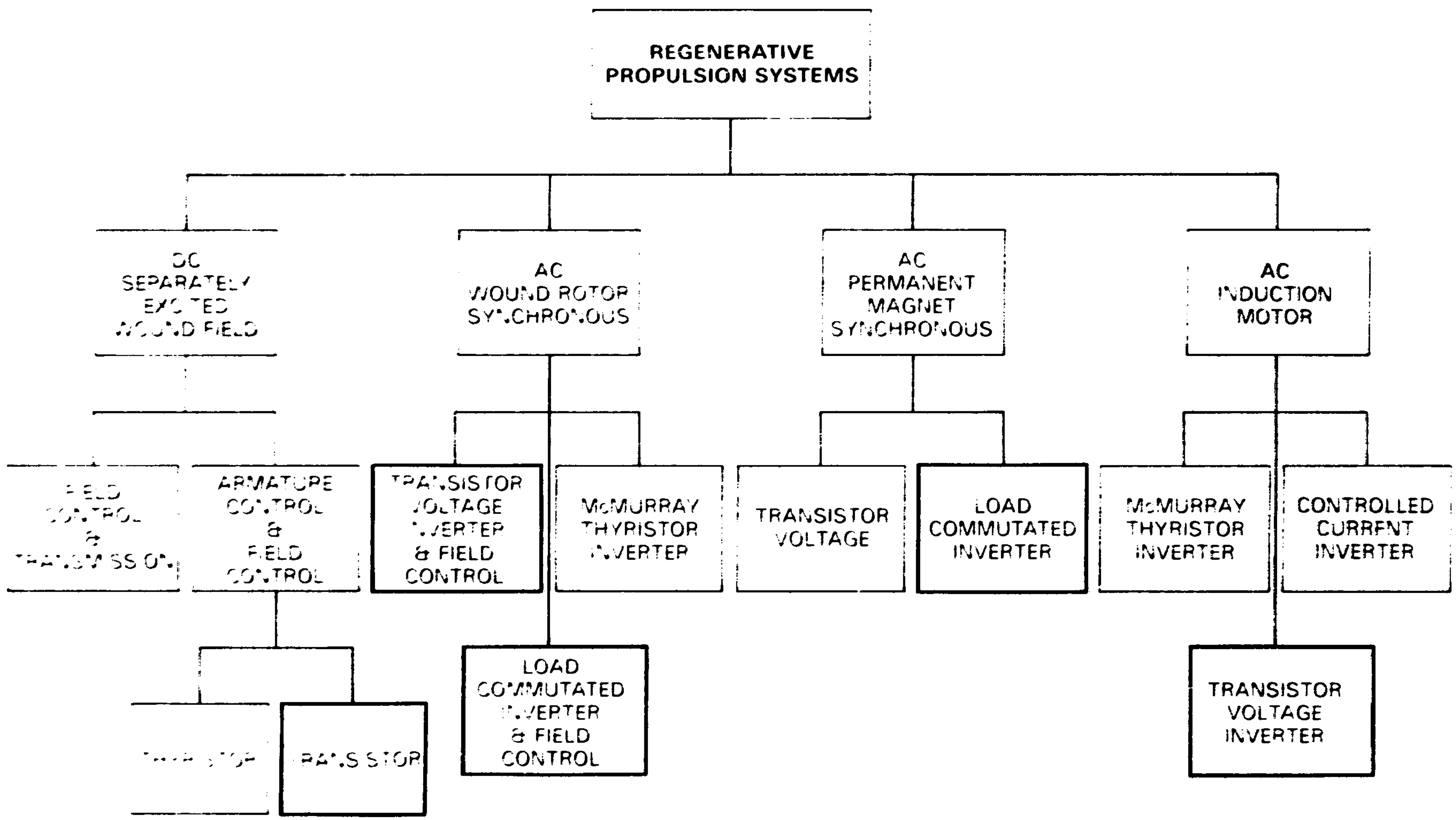


Figure 4-5. Candidate Motors and Controls

1. DC Motors - The Near-Term Electric Vehicle Program selected the wound field separately excited dc motor with transistorized chopper to be the preferred choice for dc drives. These were assigned the rating of ninety in the General Electric ac drives study. Of particular importance is the possibility of using this type of motor with field control and a shifting transmission for an alternate approach to armature control.

2. Permanent Magnet Motors, AC & DC. These were considered to be highly desirable long-range candidates in the General Electric ac Drives Study. However, these would not mature soon enough for long-scale manufacture in the mid-1980's as required by the DOE contract. This applies to both the ac and dc versions of these motors.

3. AC Synchronous Motors - Wound Field. This type of motor with either a transistorized PWM inverter or a load-commutated thyristor inverter was highly rated in the General Electric study. It was not chosen because the motor is about 20% larger and heavier than the induction motor; the motors are not as highly developed or production-ready as the induction motor; and the system cost is about 10% higher. The performance in range is essentially the same. In addition, separate field excitation is required. Rotating exciters are not considered further due to inward size, weight, and cost. Experience in application of brushes and slip rings to propulsion-type transportation has indicated this may be a source of maintenance and reliability problems.

4. AC Synchronous Motors - Inductor. These motors lend themselves quite well to driving a flywheel since they have controllable excitation on the stator, can be completely sealed and evacuated, and have high rotor inertia which can be utilized for energy storage. However, since these motors are heavier and more costly, they are not good candidates for vehicle propulsion motors.

5. AC Induction Motors. This type of motor with transistorized voltage inverter offers the best ac drive that utilizes technology that can be in high-volume manufacture during the time frame of this program. There are two alternates: a high-speed (15,000 rpm) motor with gear reducer which offers lower weight and cost but is not in present manufacture; and a lower speed (5000 rpm) motor which is a derivative of a production motor.

6. Scaling of Motor Data. A major consideration in the development of the motor subroutine for the simulations of the hybrid vehicle performance studies is that the program must be flexible enough to be used for propulsion motors of different sizes and ratings. The electric motor model used in the hybrid vehicle simulation program uses normalized parameters of a reference motor (Figure 4-6). The

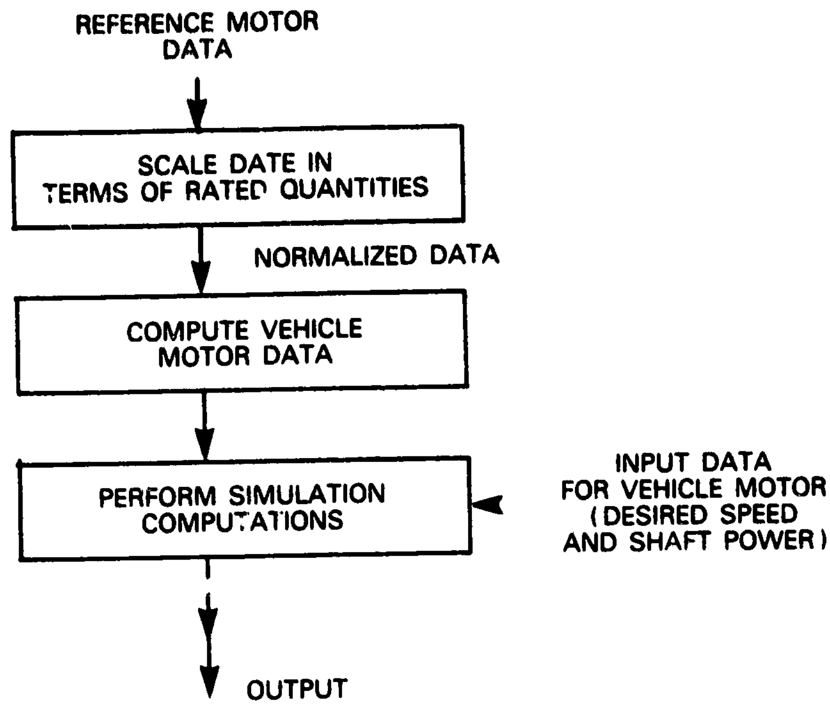


Figure 4-6. Vehicle Performance Computations

normalization of the reference motor data makes possible the use of the same data for different sized vehicles (up to ±50% duration from the size of the reference motor). The data for the two reference motors used are shown in Tables 4-1 and 4-2. The input data required of the vehicle motor is the rated speed, voltage, flux and continuous duty output power. All the motor parameters are normalized in terms of the rated voltage, current, speed, and flux of the reference motor.

Table 4-1

DC MOTOR DATA

Continuous Duty Rating	20 hp
Base Speed	2500 rpm
Max Speed	5000 rpm
Rated Current	175 A
Rated Voltage	96 V
Rated Field Current	4.9 A
Armature Winding	
Winding Resistance	0.024Ω
Winding Inductance Unsaturated	0.52 mH
Field Winding - Separately Excited	
Winding Resistance	4.3Ω
Winding Inductance Unsaturated	2.3 H
Turns per Pole	330

Torque Constant k_t = 0.352 lbft/A-megaline

Voltage Constant k_e = 0.05 V/rpm-megaline

Table 4-2

AC MOTOR DATA

Continuous Duty Rating	20 hp
Base Speed (60 Hz)	1800 rpm
Voltage per Phase (LN)	266 V
Line Current	23.32 A
Power Factor	0.87
Slip	0.0297
Stator Resistance (per Phase at 95 °C)	0.3322Ω
Rotor Resistance (per Phase Referred to Stator)	0.2466Ω
Stator Reactance	1.157Ω
Rotor Reactance (per Phase Referred to Stator)	1.184Ω
Magnetizing Reactance (per Phase Referred to Stator)	42.45Ω
Magnetizing Brance Resistance (in Series with Reactance)	1.467Ω

4.3 CONCLUSIONS

The motors and controls to be used in the detailed trade-off studies are as follows:

4.3.1 DC DRIVE SYSTEMS

- Alternate A
  - Separately excited dc motor
  - Transistorized regenerative armature chopper
  - Transistorized field control
  - Fixed-gear reduction
- Alternate B
  - Separately excited dc motor
  - Transistorized field control
  - Shifting transmission and clutch
  - Armature resistor for motor starting at no load

4.3.2 AC DRIVE SYSTEM

- Alternate A
  - AC induction motor (5000 rpm)
  - Transistorized voltage inverter
  - Fixed-gear reduction
- Alternate B*
  - AC induction motor/gear reducer (15,000/5,000 rpm)
  - Transistorized voltage inverter
  - Fixed-gear reduction

*Note: Alternates A & B are considered to be so nearly equivalent that all calculations will be made using Alternate A since detailed motor characteristics are available for Alternate A. Should Alternate B become available as a result of the NASA program, then it will be considered for this application.

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Section 4

ATTACHMENTS

Section 4 Attachment A

PROPOSED DEVELOPMENT PROGRAM ON ADVANCED ELECTRIC VEHICLE OCTCBER 1975

PROPOSED DEVELOPMENT PROGRAM

ON

ADVANCED ELECTRIC VEHICLE

for
Energy Research and Development Administration
Washington, D.C.
October 2, 1975

by
Electric Storage Battery, Inc.
General Electric Company
Triad Services, Inc.

All questions regarding this proposed program should be submitted to:

Mr. M.W. Goldman
Representative – Science and Technology
General Electric Company
777 14th Street N.W.
Washington, D.C. 20005
Telephone: 202-637-4275

ADVANCED ELECTRIC VEHICLE REQUIREMENTS

- **IMPROVED RANGE**
  - Higher Overall Drive System Efficiency
  - Improved Battery Performance, KWH/#
  - Recovery of Braking Energy
  - Reduce Battery Peak Power Drains
  - Better Aerodynamics
- **IMPROVE ACCELERATION WITHOUT AFFECTING BATTERY CAPACITY**
- **REDUCE VEHICLE WEIGHT AND COST**
  - Smaller Motor and Electronics
  - Better Battery Utilization
  - Lighter Vehicle Materials
- **IMPROVE RIDE QUALITY AND HANDLING CHARACTERISTICS**
- **MEETS SAFETY REQUIREMENTS**

ELECTRIC VEHICLE DRIVE SYSTEM OPTIONS

ENERGY STORAGE		POWER CONDITIONING UNIT	TRACTION MOTOR	TRANSMISSION	REGENERATION	COMMENT
Main	Secondary					
Lead Acid Battery	---	Chopper or Contactors	D.C. Series or Compound	---	---	Baseline of Current Tech.
Lead Acid	NiCd	Chopper	D.C. Series	Gear Change	Partial	GE DELTA, NiCd Reduces Main Battery Drain on Acceleraton
Lead Acid	---	Small Chopper-Regenerative	Small D.C. Shunt	4-Speed Shifting	Partial	Partial Regeneration to Battery, Improved Performance
Lead Acid	Flywheel Gear, D.C. Shunt Motor	---	D.C. Shunt	---	Full	Classical Ward Leonard, Field Control Chopper (Partial Regener-ation to Battery Possible)
Lead Acid	Flywheel, AC Inductor Motor	Inverter/ Rectifier	D.C. Shunt	---	Full	Modified Ward Leonard
Lead Acid	Flywheel	Small Chopper	Small D.C. Shunt	I.V.T.	Full	Flywheel for Accel-eration Secured to D.C. Traction Motor
Lead Acid	Small Flywheel	Small Inverter/ Rectifier	Small, High Speed AC Inductor Motor	High-Speed I.V.T.	Full	High Speed AC Traction Motor Allows Small Flywheel

ADVANCED ELECTRIC VEHICLE DEVELOPMENT PROGRAMS

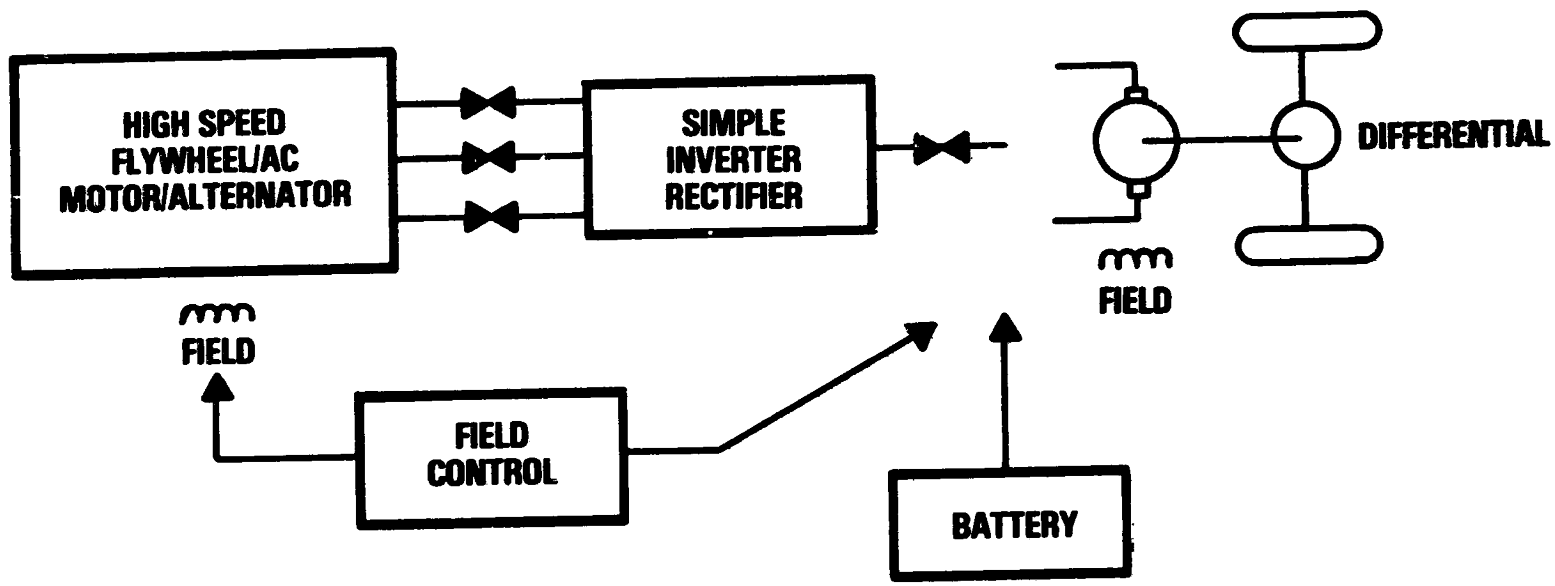
Immediate – 0 to 1 Year
Near Term – 1 to 1½ Years
Mid Term – 2 to 3 Years
Long Term – 3 to 5 Years

SUGGESTED
ADVANCED ELECTRIC VEHICLE DEVELOPMENT

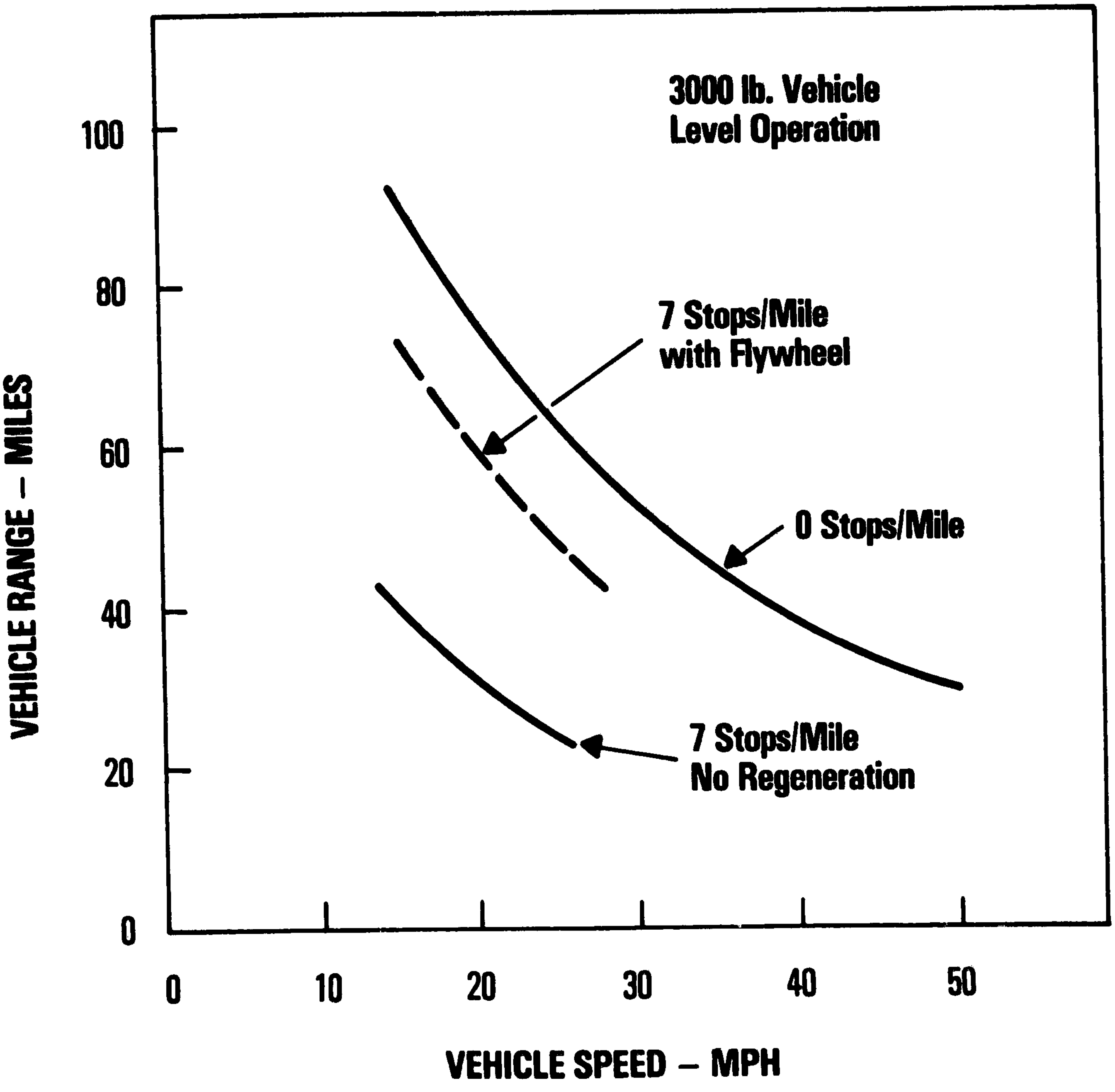
TIME FRAME	TECHNOLOGY STATUS	VEHICLE SYSTEM
Immediate	State of the Art	• Evaluate Baseline System Lead Acid - Chopper - D.C.
Near Term	Modest Advance in State of the Art	• New Vehicle - Improved Lead Acid - Small Regenerative Chopper and D.C. Shunt Motor - 4 Speed Shifting Transmission
Mid Term	Significant Advance in State of the Art	• New Vehicle - Improved Lead Acid - AC Inductor/Flywheel - Inverter/ Rectifier - D.C. Shunt Motor
		• New Vehicle - Improved Lead Acid - Small Chopper and Shunt Motor - Infinitely Variable Transmission (IVT)
Long Term	Ultimate System (Barring a Revolutionary Battery Breakthrough)	• New Vehicle - Improved Lead Acid - Small High Speed Inductor Motor - Small Inverter - High Speed IVT

BATTERY-FLYWHEEL REGENERATIVE PROPULSION SYSTEM

- **BASIC CONCEPT**

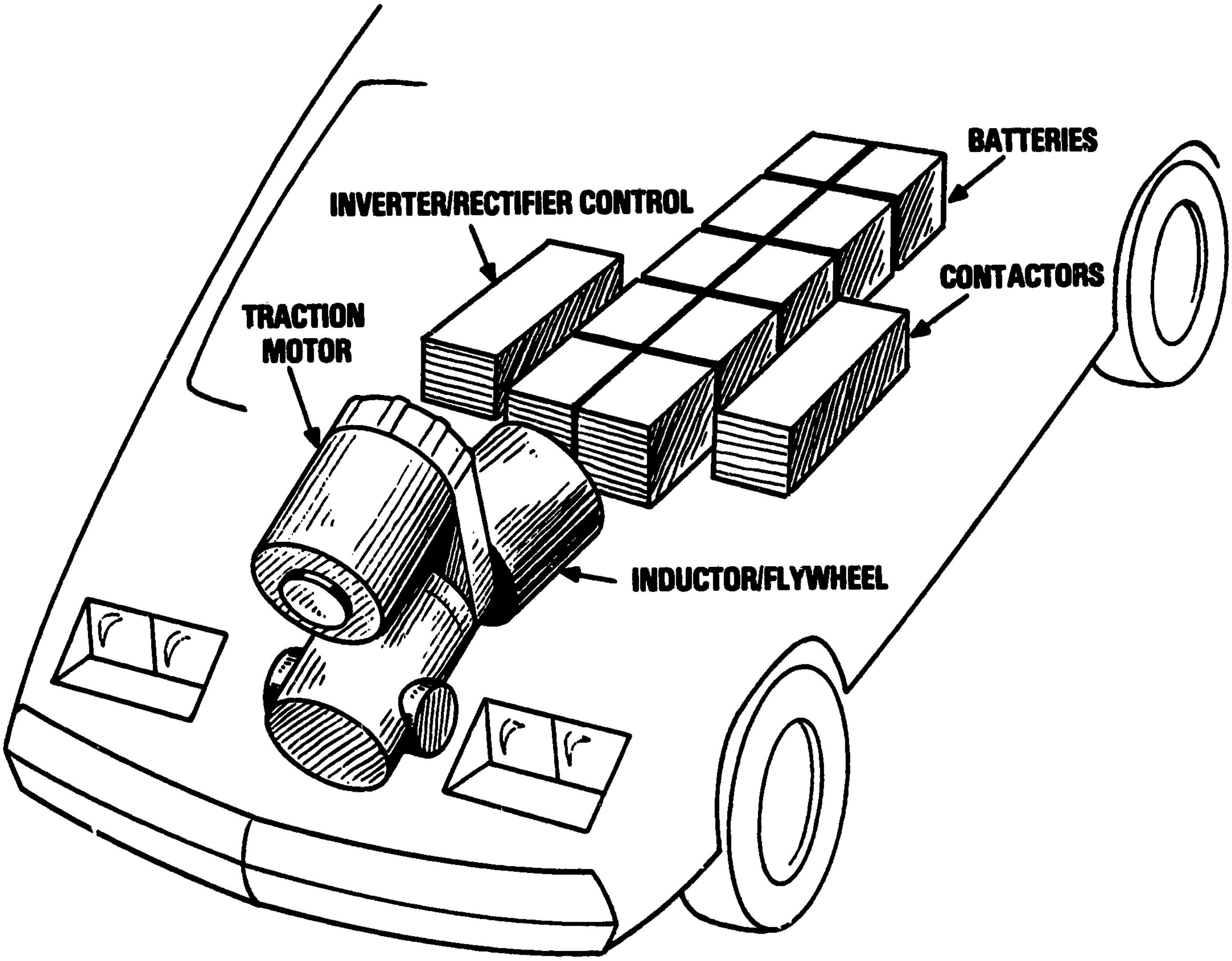


- **Battery** - for Primary Energy Storage
- **Flywheel** - Provides Acceleration Energy
  - Store Recovered Braking Energy
  - Reduces Battery Peak Current
- **Hybrid System** - Extends Vehicle Range
  - Regeneration
  - Increased Battery Capacity
  - Longer Battery Life

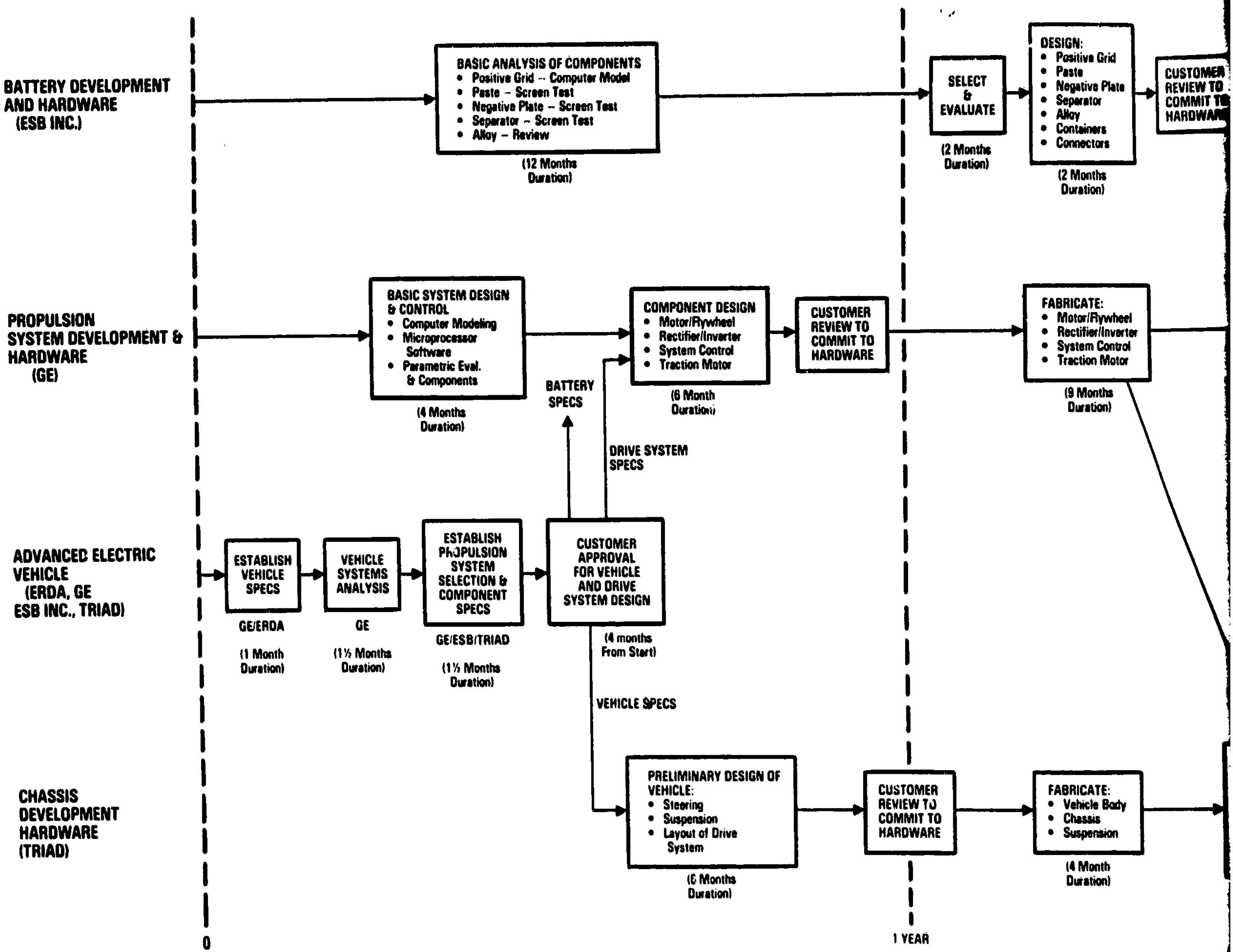


3000 lb. Vehicle
Level Operation
100
80
60
40
20
0
7 Stops/Mile
with Flywheel
0 Stops/Mile
7 Stops/Mile
No Regeneration
0
10
20
30
40
50
VEHICLE RANGE – MILES
VEHICLE SPEED – MPH

BATTERY ELECTRIC VEHICLE MID TERM DEVELOPMENT



ADVANCED ELECTRIC VEHICLE DEVELOPMENT PROGRAM



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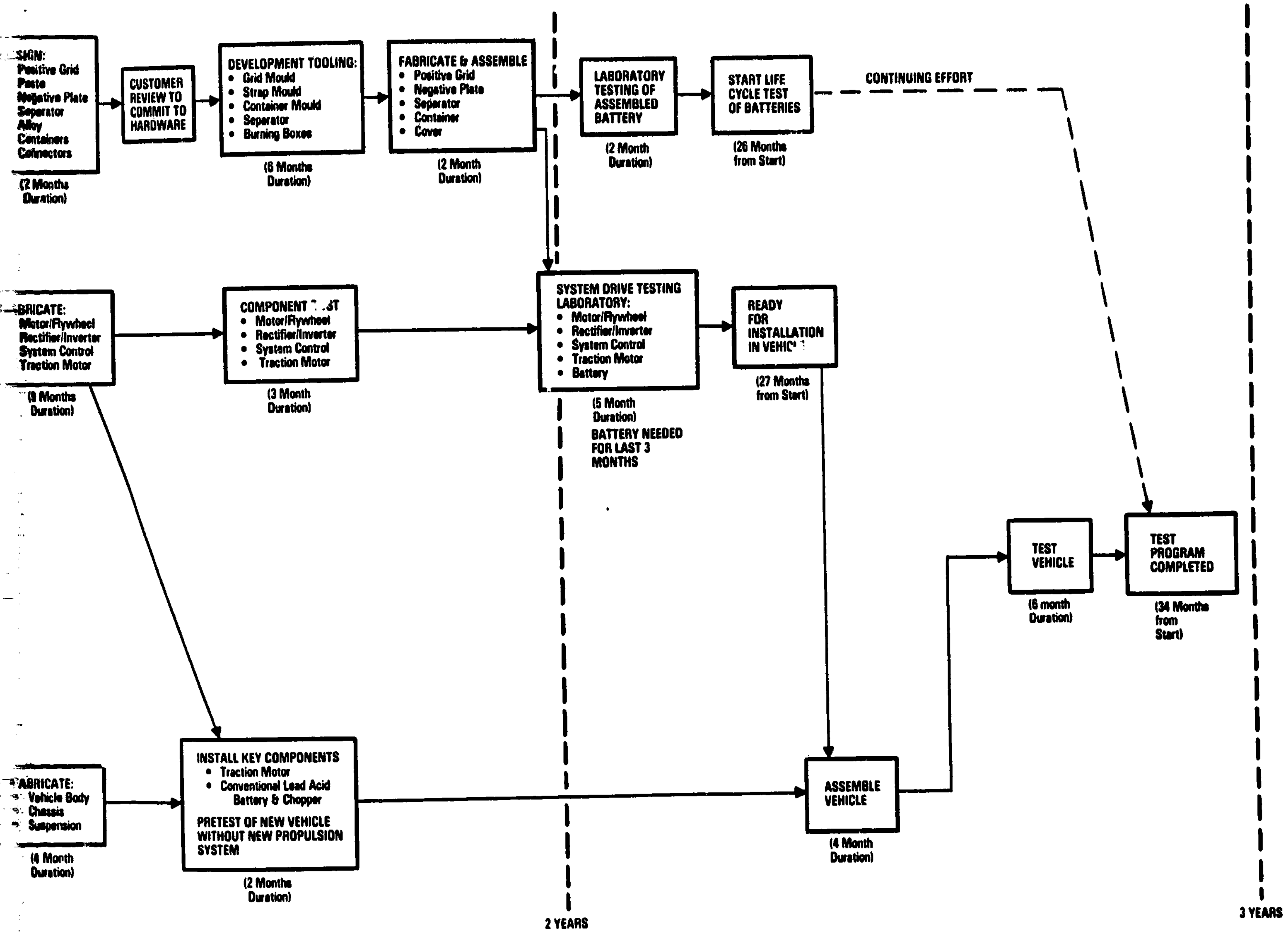


FOLDOUT FRAME 2

BUDGETARY ESTIMATES
ADVANCED ELECTRIC VEHICLE DEVELOPMENTS

TIME FRAME	TECHNOLOGY STATUS	VEHICLE SYSTEM	
Immediate	State of the Art	• Evaluate Baseline System Lead Acid - Chopper - D.C.	$ 250 K
Near Term	Modest Advance in State of the Art	• New Vehicle - Improved Lead Acid - Small Regenerative Chopper and D.C. Shunt Motor - 4 Speed Shifting Transmission	$ 500 K
Mid Term	Significant Advance in State of the Art	• New Vehicle - Improved Lead Acid - AC Inductor/Flywheel - Inverter/ Rectifier - D.C. Shunt Motor	$1,000 K
		• New Vehicle - Improved Lead Acid - Small Chopper and Shunt Motor - Infinitely Variable Transmission (IVT)	$ 750 K
Long Term	Ultimate System (Barring a Revolutionary Battery Breakthrough)	• New Vehicle - Improved Lead Acid - Small High Speed Inductor Motor - Small Inverter - High Speed IVT	$1,500 K

Section 4 Attachment B

CENTENNIAL ELECTRIC CAR

hatchback-type rear door. The front doors open out and forward on hinged links – one pivoted beneath the driver's seat, the other hinged at the toeboard. As a result, the doors can be opened fully even when the Centennial Electric is parked within 14 inches of an obstacle.

One of the prime considerations of the vehicle's design was to duplicate the "feel" of a conventional car. For example, the front seating arrangement, instrument panel, and floor-mounted, automatic shift lever are similar to those found in conventional autos. Dials on the instrument panel show the amount of energy stored in the battery (similar to a fuel gauge) and measure electric current in amperes. Rounding out the panel are the usual warning lights showing whether the power is on, the battery is charging, the lights are at high beam, or if there is a brake failure. The shift lever indicates "neutral," "park," "forward," and "reverse."

Including batteries, the Centennial Electric weighs 3,250 pounds. It stands 53.5 inches high, and is 160 inches long, 6[illegible].1 inches wide, and has a wheelbase of 92 inches. Ground clearance is six inches. Auxiliary equipment includes a gasoline-type heater, AM/FM/CB radio, and electric windshield wipers and defrosters. Fans, headlights, and other accessories operate off a standard 12-volt battery, which is connected to an on-board battery charger.

In addition to the Centennial Electric, the GE Research and Development Center presently is in the final stage of developing and building two advanced electric vehicles for the U.S. Department of Energy as part of its Near-Term Electric Vehicle Program. The two "integrated test vehicles" will contain new technology not commercially available at this time, and will have improved performance characteristics.

79GPR002

GENERAL ELECTRIC

The General Electric Company's

Centennial Electric

An Experimental Electric Vehicle

The Centennial Electric

General Electric, the world's leading supplier of motors and controls for all existing types of electric vehicles, has unveiled an experimental, subcompact-sized auto that it describes as "the electric car of today."

The four-passenger test vehicle – announced in September 1978 – was designed "from the ground up" to achieve top performance from off-the-shelf components and battery systems now commercially available in the marketplace. In honor of GE's 100th birthday, which the company celebrated in 1978, the sleek, two-toned blue vehicle has been named the "Centennial Electric."

This new test vehicle was designed to provide hard data about exactly where technology stands in the formidable quest to develop a practical electric car. It is equipped with improved lead-acid batteries, coupled with advanced solid state controls and a highly efficient electric traction motor. The vehicle is designed primarily for stop-and-go urban driving, and has an in-town range of about 45 miles between battery charges. About 11 million of the 111 million vehicles now on the nation's highways are second cars and delivery trucks used primarily for just this type of short-trip driving.

Electrics still must demonstrate that they can compete with conventional vehicles in such areas as reliability, safety, handling characteristics, and driver and passenger comfort, along with initial purchase price and trade-in value. A primary reason for building the Centennial Electric was to establish just how close existing electrical and electronic components and battery systems can approach these goals.

The development of a practical electric car is an obvious response to the world's dwindling petroleum reserves. Although GE has no plans at this time to manufacture or market electric vehicles, it foresees long-range opportunities as a supplier of components for this emerging market.

GE's Centennial Electric is literally "a laboratory on four wheels," designed so that its systems and components can be readily replaced by improved versions that come out of GE laboratories and product departments. One of GE's future plans, for example, is to test an AC drive system in the vehicle.

GE's front-wheel-drive electric was produced in a three-year project headed by the company's Research and Development Center in Schenectady, N.Y. The drive motor, solid state controls, plastic windows and other plastic parts, headlamps, and numerous other components were supplied off-the-shelf by more than a dozen GE product departments.

Triad Services, Inc., a leading electric automobile design firm based in Dearborn, Mich., designed and built the low-slung test car to GE specifications as an integrated concept, with all elements keyed to the GE propulsion system.

The car is powered by 18 six-volt, lead-acid batteries made especially for GE's Electric Vehicle Systems Operation, Salem, Va., by Globe-Union Inc., Milwaukee, Wisc. They are derived from the deep-discharge batteries now used commercially to power golf carts and forklift trucks, and can be recharged in six to eight hours by plugging them into a 220-volt electrical outlet.

Initial tests show that the vehicle has a range of 75 miles at a constant 40 miles per hour, a cruising speed of 55 mph, and a passing speed of up to 60 mph. It can accelerate from zero to 30 mph in nine seconds. By way of comparison, a conventional gasoline-powered car of similar size and weight can reach the same speed in about six seconds. Although the car is not for sale, it was designed to sell for about $6,000 if 100,000 of them were manufactured annually in one plant.

The Centennial Electric is one of only a handful of electric vehicles that have been designed from scratch.

Many existing electrics are modifications of gasoline-powered compacts or are essentially "glorified" golf carts. For example, GE's test car has no grill because there is no radiator to cool. It has a low center-of-gravity because 1,225 pounds of batteries are slung on a movable trolley beneath the vehicle and run nearly its full length. The 24-horsepower DC series traction motor is tilted at an angle because the geometry of the drive train is simpler.

Among the features of the GE electric is the seating arrangement for rear-seat passengers. To keep the car low to reduce air drag and to permit easier entry and exiting, the seats face to the rear and are entered through a

FACT SHEETS

GE-100 CENTENNIAL ELECTRIC VEHICLE

VEHICLE ORIGIN

• Developer	GE-CRD
• Propulsion System, Electrical Components, Plastics	General Electric Co.
• Battery	Globe-Union, Inc.
• Vehicle Design & Fabrication	Triad Services, Inc.

VEHICLE DESCRIPTION

Type	3-Door Commuter
Color	Two-tone Blue
Capacity	4 Adults
Curb Weight (including battery)	3250 #
Gross Weight	3850 #
Frontal Area	19.9 ft^2
C_D - Drag Coefficient	
- 0° Yaw	0.337
- Weighted for Yaw	0.367
Wheel Base	92 in.
Width	66.1 in.
Length	160 in.
Height	53.6 in.
Ground Clearance	6 in.

FACT SHEETS

GE-100 CENTENNIAL ELECTRIC VEHICLE

VEHICLE SPECIAL FEATURES

- Designed from ground up as Electric Vehicle
  - reduced aerodynamic drag
  - designed to meet Federal Motor Vehicle Safety Standards

- Utilizes commercially available components

- Excellent handling
  - front wheel drive
  - low center of gravity
  - low polar moment of inertia
  - good front to rear weight balance

- Unique packaging
  - batteries in separate tunnel
  - batteries removable as single unit
  - side doors open parallel to body (14" clearance)
  - full height gull wing rear hatch
  - rear facing back seats with ample room for two full-sized adults

- Minimum difference in driving "feel"
  - location of controls
  - similarity of instruments
  - similar handling characteristics

- Selected materials
  - stainless steel underbody
  - mild steel body
  - Lexan® polycarbonate resin side and rear windows
  - Lexan® headlamps covers
  - Noryl® thermoplastic resin dashboard and console

*Lexan® and Noryl® are registered trademarks of General Electric Company

FACT SHEETS

GE-100 CENTENNIAL ELECTRIC VEHICLE

PERFORMANCE (Measured)

Range

Urban - SAE J227a Schedule D	45 miles
40 MPH Constant Speed	75 miles
55 MPH - Cruising (calculated)	50 miles

Acceleration

0 - 30 MPH	9 sec
0 - 40 MPH	14 sec
0 - 50 MPH	30 sec

Speed

Cruising	55 mph
Passing	60 mph

Grade

Maximum	30%

FACT SHEETS

GE-100 CENTENNIAL ELECTRIC VEHICLE

DRIVE TRAIN DESCRIPTION

Armature Chopper & Controls	EV-1 (GE)
Chopper Efficiency	> 95%
DC Series Motor - 24 HP, 230#	5BT2364 (GE)
Maximum Motor Efficiency	86%
Propulsion Battery (3-year life) 108 V - 1225 #	(18) GC-419 (6V lead-acid) Globe-Union
Battery Recharge Time 230 V - 30 A	6 - 8 hours
Power Wiring Resistance	0.002 Ω
Drive Train Mechanical Efficiency	98%
Fixed Gear Ratio	5.62 : 1
Motor/Vehicle Speed Ratio	80.5 RPM/MPH

FACT SHEETS

GE-100 CENTENNIAL ELECTRIC VEHICLE

GE PRODUCTS	DEPARTMENT
• EV-1 Controls, Contactors	Industry Control Dept.
• 5BT2364 Motor	DC Motor & Gen. Dept.
• Lexan® Windows* & Headlamp Covers	Plastic Sales Dept.
• Noryl® Instrument Panel, Dash, Console, Wheel Covers	Plastic Sales Dept.
• Connectors, Plugs, Receptables	Wiring Devices Dept.
• Instruments & Shunts	Meter Dept.
• Wire & Cable	Wire & Cable Dept.
• Radio	Audio Products Dept.
• Head, Rear & Marker Lights	Miniature Lamp Dept.
• Interior Surface Finish	Laminated & Insulating Products Dept.
• Microswitches & Switchettes	Appliance Control Products Dept.
• Lubricants & Sealants	Silicone Products Dept.

* Windshield by Pittsburgh Plate Glass

FACT SHEETS

GE 100 CENTENNIAL ELECTRIC VEHICLE

ENERGY CONSUMPTION - KWh/Mile

(Battery and Charger Efficiency ≈ 70%)

Type of Driving	Energy Consumption (KWh-mi) Input to Charger From Wallplug	From Battery
• SAE J227a - Schedule D	0.429	0.300
• 40 MPH Constant Speed	0.285	0.193

VEHICLE SUMMARY DATA SHEET

1.0 Vehicle manufacturer General Electric/Triad Services, Inc.

2.0 Vehicle GE Reference Electric Vehicle

3.0 Price and availability One of a kind - experimental prototype $250K estimated replacement value

4.0 Vehicle weight and load

4.1 Curb weight, kg (lbm) 1475 (3250)

4.2 Gross vehicle weight, kg (lbm) 1747 (3850)

4.3 Cargo weight, kg (lbm) -0-

4.4 Number of passengers 4

4.5 Payload, kg (lbm) 272 (600)

5.0 Vehicle Size

5.1 Wheelbase, m (in.) 2.34 (92)

5.2 Length, m (in.) 4.06 (160)

5.3 Width, m (in.) 1.68 (66.1)

5.4 Height, m (in.) 1.36 (53.6)

5.5 Head room, m (in.) .97 (38.3)

5.6 Leg room, m (in.) 1.06 (41.9)

5.7 Frontal area, m^2 (ft^2) 1.77 (19)

5.8 Road clearance, m (in.) .15 (6)

5.9 Number of seats 4

6.0 Auxiliaries and options

6.1 Lights (number, type, and function) Dual Beam Headlights (4), Front Parking & Direction, Front Side Markers (Parking & Direction), Rear Tail Lamp Assembly (Backup, Taillight, Directional, Stop), Rear Lic. Plate Lamp, Rear Side Markers (Tail) - Dome light, 2 courtesy lamps, Dash cluster illumination lamps.

6.2 Windshield wipers — Non-Depressed Park — Yes
6.3 Windshield washers — Integral with wiper motor — Yes
6.4 Defroster — Gas Heater - Ram air & blower — Yes
6.5 Heater — Gas Heater - Ram air & blower — Yes
6.6 Radio — No
6.7 Fuel gauge — Battery state of charge — Yes
6.8 Ampmeter — Yes
6.9 Tachometer — No
6.10 Speedometer — BDO — Yes
6.11 Odometer — + Trip Odometer — Yes
6.12 Right- or left-hand drive — LH
6.13 Transmission — Direct Drive — No
6.14 Regenerative braking — No
6.15 Mirrors — Interior Rear View & L&R Exterior — Yes
6.16 Power steering — No
6.17 Power brakes — No
6.18 Other — Radio - AM/FM/Stereo CB Tranceiver — Yes

7.0 Batteries

7.1 Propulsion batteries

7.1.1 Type and manufacturer GC-419 - Globe-Union, Inc. Lead-acid
7.1.2 Number of modules — 18
7.1.3 Number of cells — 3 each — 54
7.1.4 Operating voltage, V — 6 volts each — 108
7.1.5 Capacity, Ah — 75A for 106 minutes — 132.5
7.1.6 Size of each battery, m (in.) L = 0.26 (10 3/8), W = 0.18 (7 3/16), H = 0.29 (11 11/32)
7.1.7 Weight kg (lbm) per module 30.9 (68.1)
7.1.8 History (age, number of cycles, etc.) New - Few cycles operating vehicle during shakedown

7.2 Auxiliary battery

7.2.1 Type and manufacturer Snowmobile Garden Tractor Globe-Union, Inc. - Lead-Acid
7.2.2 Number of cells — 6

7.2.3 Operating voltage, V 12

7.2.4 Capacity, Ah 20 hour rate 30

7.2.5 Size, m (in.) L = 197 (7 3/4), W = 130 (5 1/8), H = 187 (7 3/8)

7.2.6 Weight, kg (lbm) 10 (21.8)

8.0 Controller

8.1 Type and manufacturer SCR EV-1C General Electric

8.2 Voltage rating, V 84 - 144 volts

8.3 Current rating, A 850 Peak, 375 Max Avg Batt, 150-200 Motor on duty cycle

8.4 Size, m (in.) L = 36.56 (14), W = 20.47 (8.06), H - 17.68 (6.96) - H over hinged control 27.89 (10.98)

8.5 Weight, kg (lbm) 23.1 (51)

9.0 Propulsion motor

9.1 Type and manufacturer DC Series 5BT2364 General Electric

9.2 Insulation class F

9.3 Voltage rating, V 108

9.4 Current rating, A 195

9.5 Horsepower (rated), kW (hp) 17.9 (24)

9.6 Size, m (in.) OD = 0.29 (11.38), L (over shaft)=0.51 (20.00)

9.7 Weight, kg (lbm) 104.36 (230)

9.8 Speed (rated), rpm 3000

10.0 Battery charger

10.1 Type and manufacturer Lab Model - Ferro Resonant, GE-CRD

10.2 On- or off-board type off

10.3 Input voltage required, V 1 - Ø 220V

10.4 Peak current demand, A 27.5A

10.5 Recharge time, h 6 - 8

NOTE: On-Board Accessory Charger

- .1 - EVA DC-DC Transformer Isolated
- .2 - On Board
- .3 - 85 - 125V DC (Main Battery)
- .4 - 2.5A
- .5 - 4 - 6 hours
- .6 - L = .32 (12.5), W = 0.1 (4), H = 0.08 (3)
- .7 - 2.7 kg (6)
- .8 - Yes, Regulated

10.6 Size, m (in.) L = 0.38 (14), W = 0.28 (11), H = 0.28 (11)

10.7 Weight, kg (lbm) 43 (95)

10.8 Automatic turnoff feature Adjustable Timer - 12 hour max.

11.0 Body

11.1 Manufacturer and type Triad Services, Inc. - Hatchback

11.2 Materials Stainless steel underbody, Steel & Fiberglass body

11.3 Number of doors and type 2 parallelogram linkage side, 1 gull wing rear hatch

11.4 Number of windows and type glass windshield, mar resistant Lexan® - 2 fixed in side doors, 2 sliding in side doors, 2 fixed in rear quarters, 1 fixed in rear door

11.5 Number of seats and type 2 front full buckets, 2 removable rear-facing jump seats

11.6 Cargo space volume m^3 (ft^3) to window level 1.36 (48)

11.7 Cargo space dimensions, m (ft) L = 1.83 (6), W = 1.22 (4), H = 0.61 (2)

12.0 Chassis

12.1 Frame

12.1.1 Type and manufacturer unibody - Triad Services, Inc.

12.1.2 Materials Stainless steel backbone, fiberglass panels

12.1.3 Modifications New

12.2 Springs and shocks

12.2.1 Type and manufacturer Spring - new coils, shocks - Monroe take-aparts

12.2.2 Modifications New

12.3 Axles

12.3.1 Manufacturer Audi and Subaru

12.3.2 Front Audi Fox front wheel drive

12.3.3 Rear Subaru hubs, no axle

12.4 Transmission

12.4.1 Type and manufacturer New - Morse HyVo Chain Drive, Chrysler parking pawl, BW differential

12.4.2 Gear ratios Chain 1.36 to 1.0, Differential 4.135 to 1

12.4.3 Driveline ratio Overall 5.620 to 1

12.5 Steering

12.5.1 Type and manufacturer New - Triad Services, Inc.

12.5.2 Turning ratio 18.5 to 1

12.5.3 Turning diameter, m (ft) 9.75 (32)

12.6 Brakes

12.6.1 Front Inboard Chevelle with copper drums

12.6.2 Rear Subaru drums

12.6.3 Parking Vega coupled to front Chevelle

12.6.4 Regenerative None

12.7 Tires

12.7.1 Manufacturer and type Michelin radial

12.7.2 Size B78 - 13

12.7.3 Pressure, kPa (psi):

Front 165.5 - 179.3 (24 - 26)

Rear 165.5 - 179.3 (24 - 26)

12.7.4 Rolling radius, m (in.) 0.30 (11.8)

12.7.5 Wheel weight, kg (lbm):

Without drum Front brakes inboard - wheel 6.81 (15)

With drum - wheel & tire 14.07 (31)

12.7.6 Wheel track, m (in.):

Front 1.38 (54.5)

Rear 1.47 (58.0)

13.0 Performance

13.1 Manufacturer-specified maximum speed (wide-open throttle), km/h (mph) 96.5 (60)

13.2 Manufacturer-recommended maximum cruise speed (wide-open throttle), km/h (mph) 88.5 (55)

13.3 Tested at cruise speed, km/h (mph) 96.5 (60)

Section 4 Attachment C

ELECTRIC VEHICLE AC DRIVE STUDY

Section 4 Attachment C

ELECTRIC VEHICLE AC DRIVE STUDY

In late 1977 General Electric Corporate Research and Development undertook a study of promising ac traction motor drives both medium-term and long-range. The study recommended an ac induction motor with transistor voltage inverter for development in the medium-term and a permanent magnet synchronous disk motor with thyristor load-commutated inverter for long-range development. The medium-term ac induction motor is being developed on NASA Contract Number DEN3-59. The ac PM synchronous motor is being developed on a General Electric-funded program.

WORK STATEMENT FOR ELECTRIC VEHICLE AC DRIVE STUDY

OBJECTIVE

This study will identify the most promising ac traction motor electric drive system concepts for an electric automobile for medium-term development starting in 1978. Exploratory longer-term concepts will be identified and the more promising examined.

APPROACH

At least three different vehicle duty cycles will be used to identify the range of applicability of the various drive concepts. The three principal duty cycles are:

- The SAEXJ227D duty cycle (as the standard) (Figure C-1)
- The SAEXJ227A duty cycle which has additional stop-start duty typical of delivery vehicles
- A steady speed, few stop-type duty for commuter car applications

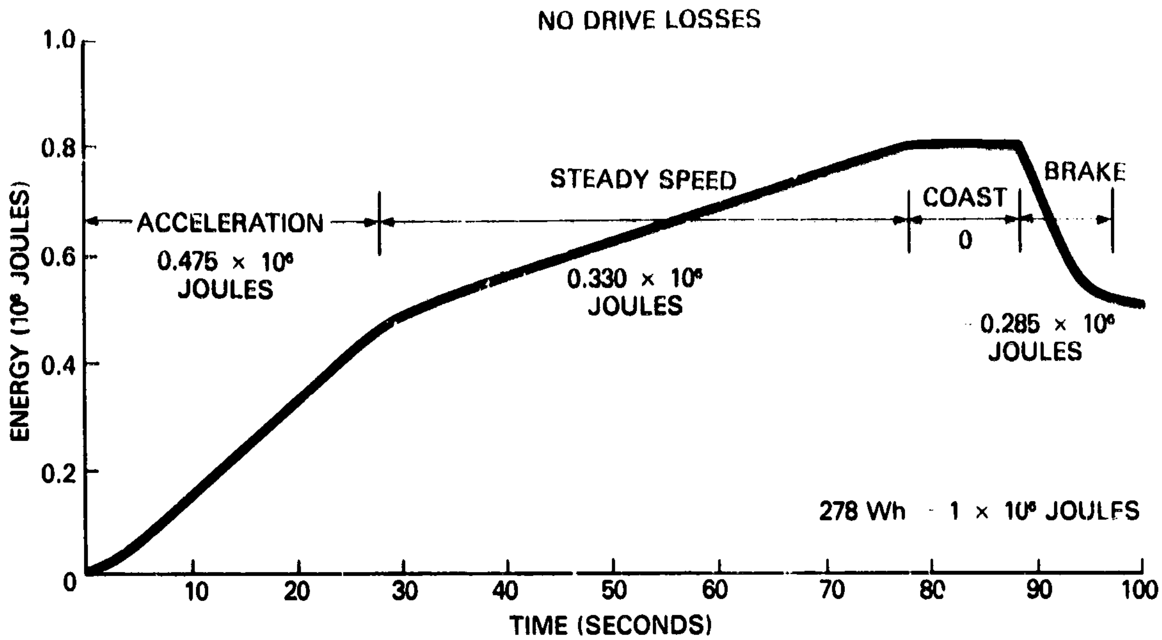


Figure C-1. Energy for J227, a Schedule D Driving Cycle

It is expected that some of the drive concepts can be optimum for one type of duty, such as steady speed running, while others will be better for other duty cycles such as stop-start running. The GE/ERDA 3000-pound electric automobile will be used as the basic vehicle for which each drive will be designed. All drives will meet the ERDA performance goals.

CONSTRAINTS

The drives will consist of the energy source, a power converter, an ac electric traction motor(s), and a mechanical drive coupling the motor to the wheels.

Three electrical energy source systems will be considered: a lead-acid battery, a flywheel, and a hybrid flywheel-battery system.

The motor types to be considered will include:

- Synchronous motor
  - Wound rotor
  - Inductor
  - Permanent magnet
- Inductor motor

Both the conventional and disc forms will be examined.

Power converters to be examined will include:

- Voltage converter
- Current converter
- Transistors
- Thyristors

The mechanical drives to be considered will include:

- Fixed-gear reduction
- Infinitely variable transmission
- Direct drive (wheel motors)

The performance of the candidate drive systems will be evaluated using a simplified vehicle performance program to determine:

- Drive efficiency
- Drive weight
- Range
- Vehicle performance

An estimate of the weight and cost of the candidate systems will be provided on a comparison rather than absolute basis. A

subjective assessment of other drive system characteristics, such as operational complexity, reliability, fabricability, etc. will be made.

TASKS

Task 1 - Gather existing information and build background.

Task 2 - Establish the electric vehicle performance baseline and specify the three duty cycles.

Task 3 - Design in some detail an ac induction motor for the drive and evaluate the motor weight change required as a function of the duty cycle and type of mechanical transmission used.

Task 4 - Select and examine other types of traction motors including advanced concepts based on the detailed design of Task 3. Estimate the costs, weights and efficiencies.

Task 5 - Design power conversion apparatus for each type of motor in enough detail to estimate size, weight, costs, performance, and efficiency.

Task 6 - Assemble the results of the drive evaluation into a matrix of drive system candiates and derive a system "cost" evaluation equation to rank the resulting systems.

Task 7 - Prepare a report.

II. AC DRIVE STUDY METHODOLOGY

The initial screening considered the following:

1. Motor variations
   - Synchronous
     - PM disc
     - PM conventional
     - Wound field on rotor
     - Inductor (field on stator)
   - Induction
     - Cast rotor
   - DC separately excited motor (reference design)
2. Power converter variations
   - Inverter suitable for each motor
     - Thyristor
       - .. McMurray voltage
       - .. Auto - sequential current
       - .. Third harmonic load commutated
   - Transistor
       - .. Voltage
       - .. Current
   - DC transistor regenerative chopper with bypass and field control (reference design)
3. Gearing
   - Fixed gearing
     - Limit in speed to 15,000 rpm

.. Mist bearings

.. Double gear reduction

● Gear changing

- Fixed gear changes

.. Three or four-to-one speed ratio for motor

Preliminary designs of motors and controls were made to determine cost, weight, efficiency, and vehicle range for each. Quite early in the study gear chan[illegible] versus fixed-gearing was determined a stand-off when one considered the weight, cost, and gear efficiency of the transmission, as well as the more complex control. This is aggravated by the fact that the motor and control would be sized by the maximum power requirements which occur when passing at high speeds and when maintaining high speed on a grade. These factors negated the possibility of reducing propulsion equipment, weight, and cost for accelerations at low speeds through gear changing.

The inductor motor was rejected early in the study because of weight, cost, inertia, and low efficiency. It is ideally suited for operating with an energy storage flywheel but is not viable as a propulsion motor.

RESULTS OF THE STUDY

The results of the study are summarized in Tables C-1 through C-4 and in Figures C-2 through C-5.

Table C-1

RELATIVE MOTOR AND EXCITER COSTS

Motor and Control Type	Cost ($)	Exciter Cost ($) Inverter	Field Chop-per	Total Cost ($)	Motor and Exciter Relative Costs
Separately Excited with dc Chopper	872	675	100	1647	1.00
McMurray ac Induction Motor	200	2547	-	2747	1.67
McMurray ac Wound Synchronous Motor	242	2547	100	2889	1.75
Load-Commutated Inverter's & ac Wound Synchronous Motor	242	1537.5	100	1779.5	1.08*
Load-Commutated Inverter PM Synchronous Motor Including Field Exciter	200	1537.5	100	1737.5	1.05*
Controlled Current ac Induction Motor	200	4897	100	5097	3.09
Transistor Voltage ac Induction Motor	200	1425	100	1625	0.99*
Transistor Voltage ac Wound Synchronous Motor	242	1425	100	1767	1.07*
Load-Commutated Inverter Improved PM Synchronous Improved Capacity	100	1537.5	100	1637.5	0.99*
Transistor Voltage PM Synchronous Motor with Real dc Motor Price	200	2850	100	3050	1.85
Load-Commutated Inverter ac Inductor Motor	466	1537.5	100	2103.5	1.28
Transistor Voltage ac Induction Motor (5000 rpm)	276	1425	100	1701	1.03*

*Lowest cost options

Table C-2

EFFECT OF MOTOR TYPE AND CONTROL ON RANGE CHANGE

Motor and Control Type	Weight			Efficiency			Range (Miles)	Range Change (%)
	Motor	PCU	Total	Motor	PCU	Combined		
dc Chopper	218	49	267	0.84	0.97	0.81	60.0	0
McMurray I ac Induction Motor (1500 rpm)	100	140	240	0.935	0.90	0.842	62.8	+4.67
McMurray ac-wound synchronous motor	121	140	261	0.93	0.90	0.837	62.1	+3.5
Load-Commutated Inverter ac-wound synchronous Motor	121	150	271	0.93	0.925	0.86	63.6	+6.0
Load-Commutated Inverter PM Synchronous Motor Including Field Exciter	100	150	250	0.935	0.925	0.865	64.4	+7.33*
Controlled Current ac Induction Motor (15,000 rpm)	100	423	523	0.935	0.905	0.846	58.6	-2.33
Transistor Voltage I ac Induction Motor (15,000 rpm)	100	87	187	0.935	0.945	0.884	66.9	+11.50*
Transistor Voltage ac-wound Synchronous Inverter	121	87	208	0.93	0.945	0.879	66.2	+10.33*
Load-Commutated Improved PM Synchronous Motor Improved Capacity	50	100	150	0.96	0.925	0.888	67.9	+13.2
Transistor voltage PM Synchronous Motor with Real dc Motor Price	100	174	274	0.935	0.918	0.858	63.4	+5.7
Load-Commatated ac Inductor Motor	233	150	383	0.90	0.925	0.833	62.1	+3.5
Transistor Voltage ac Induction Motor (5000 rpm)	138	87	225	0.925	0.945	0.874	65.8	+9.71*

*Highest range options

Table C-3

MOTOR DATA

Motor Type	Weight lb	Average Efficiency	Cost ($)
dc Commutator	218	0.84	872
ac Induction High-Speed Motor (15,000 rpm) + Gear	100	0.935	200
ac Rotating Field Synchronous Motor	121	0.93	250
ac PM Motor	100	< 0.935	200
ac Inductor* Motor	233	0.90	466
ac Induction* Low-Speed Motor (5000 rpm)	138	0.925	276

*ac Inductor and ac Induction (5000 rpm) added later on same basis

Table C-4

POWER CONVERTER DATA

Power Converter Type	Weight (lb)	Average Efficiency (%)	Cost ($)
dc Chopper with Bypass	49	97.0	775
ac Transistor Inverter for Induction Motor	87	94.5	1425
ac SCR McMurray Inverter	140	90.0	2547
ac SCR Load-Commutated Inverter	150 (125, measured)	92.5 (93.0)	1538
ac SCR Current Inverter (ASCI)	423	90.5	4897
ac Transistor Inverter for PM Motor	174	91.8	2850

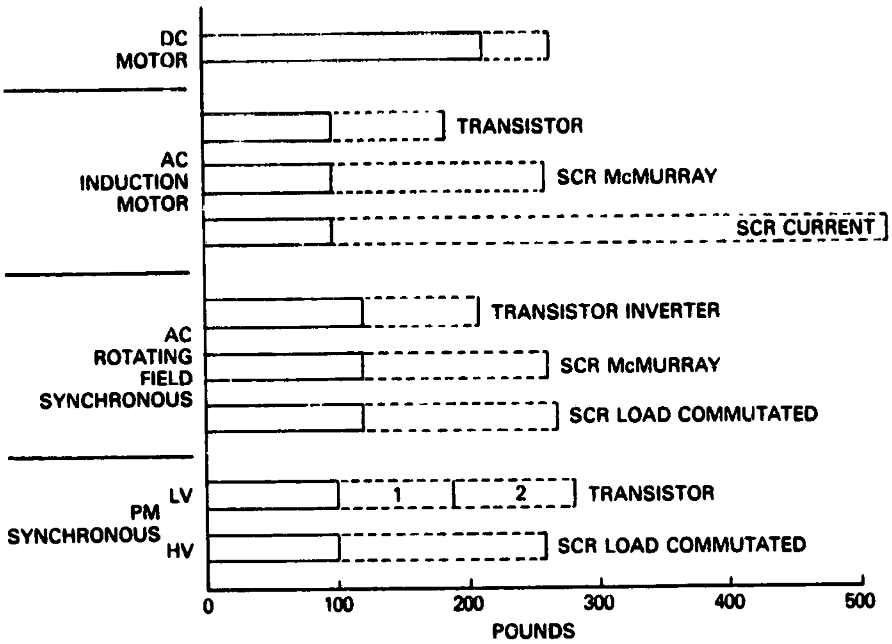


Figure C-2. Influence of Motor and Control on System Weight

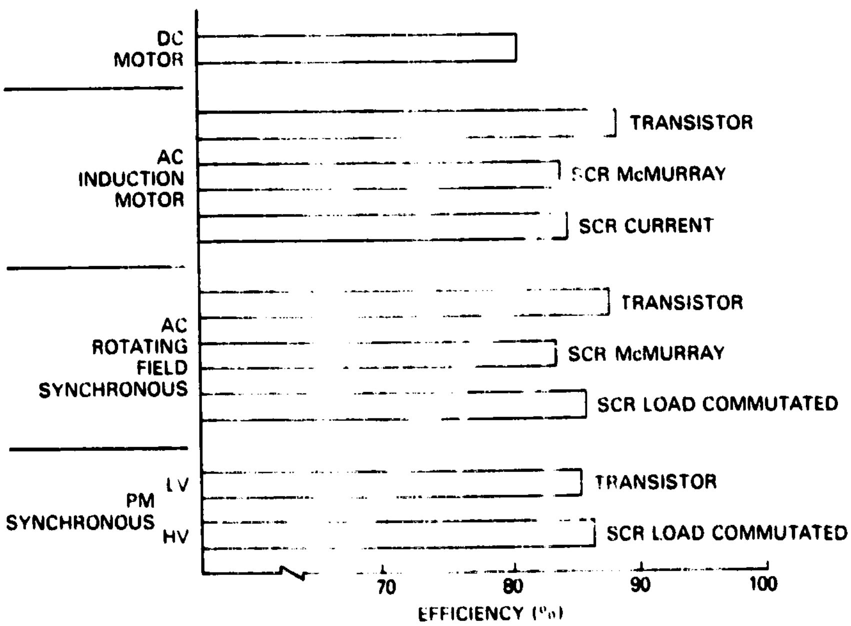


Figure C-3. Influence of Motor and Controller on System Efficiency

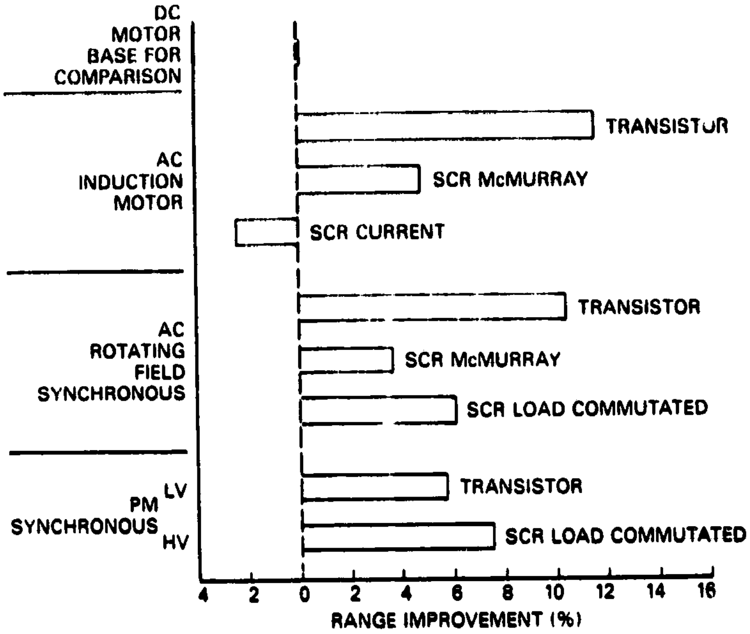


Figure C-4. Influence of Motor and Controller on ac – System Range Improvement over dc System

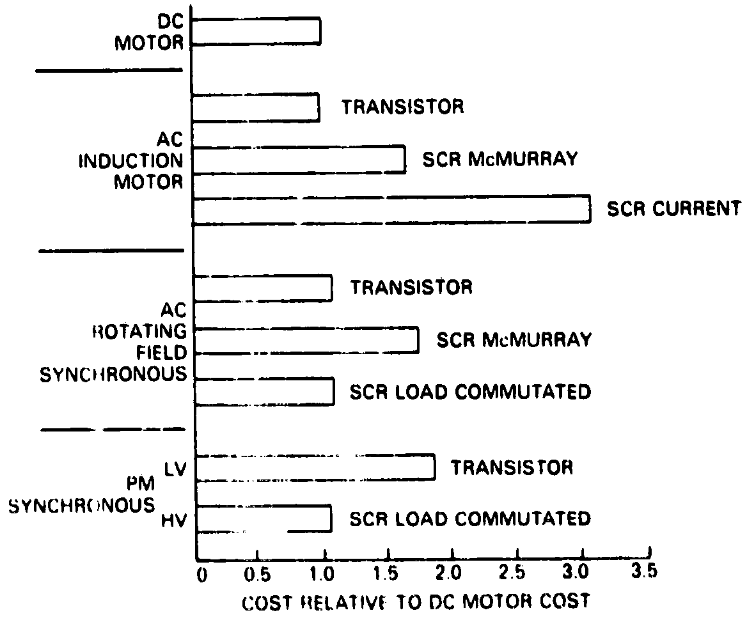


Figure C-5. Relative Cost of Motor and Control Options

III. RECOMMENDATIONS

NEAR-TERM

For the near-term the induction motor with a transistor inverter is recommended. The induction motor features include lightweight, high-efficiency, rugged construction, and low cost. The transistor inverter features lightweight, high-efficiency power modules.

Developments recommended include:

- High-power transistors
- Simple base drive
- PWM generator
- Control strategy to minimize currents

FAR-TERM

For the far-term an innovative PM synchronous motor with a load-commutated SCR inverter is recommended. The PM synchronous motor would feature low magnetic loss. A feature of the load-commutated SCR inverter would be its high-voltage capability.

Developments recommended include:

- Theory of motor design
- Mechanical construction designs
- Smooth-starting capability with load commutation

Section 4 Attachment D

PROPULSION SYSTEM DESIGN TRADE-OFF STUDIES

Section 4 Attachment D

PROPULSION SYSTEM DESIGN TRADE-OFF STUDIES

In early November 1978, preliminary evaluation of the electric propulsion requirements for the hybrid vehicle were established. Based on the recommendations of the General Electric ac drives study, an ac induction motor with transistor voltage inverter was selected as the preferred ac drive. The separately excited motor with transistor regenerative armature chopper with field control or the separately excited dc motor with a shifting transmission and field control were selected as the preferred dc drives. These three systems were to be compared in the detailed trade-off studies.

For purposes of the study, an induction motor of a more conventional speed range was chosen for evaluation. This motor, the Tri Clad 700 ac severe duty, energy power design (Reference 14), is in volume production and can be modified for electric vehicle duty as was the dc motor which is a modified version of the industrial truck motors (Reference 12). Should the high-speed ac induction motor program be as successful as anticipated and should the motor be put in high-volume production, then it can be substituted for the lower speed system for slightly improved weight.

I. SUMMARY OF DRIVE MOTOR STUDIES

Information in this subsection was prepared to aid in the selection of a drive motor. The procedures and methodology presented are to serve as a guide only toward motor selection. Data pertinent to a specific vehicle would have to be used in place of the data used to illustrate an example of how the motor calculations are made. The material on motors was prepared by W.R. Oney, General Electric Corporate Research and Development.

Figure D-1 is the "Maximum Drive Shaft Torque Specification for a Nominal Design "Motor" with:

- Maximum torque = 100 lb-ft
- Corner point spaced = 2400 rpm
- Maximum speed = 6000 rpm
- Constant power = 2400 to 6000 rpm

Figure D-2 is a general specification for drive shaft (DS) torque where the variables are T_{MAX} (maximum torque), N_O (corner point and base speed), N_{MAX} (maximum rpm), and S_{MAX} (maximum per rpm and speed which is 60 mph). The corner point may vary $\pm 25\%$ in both rpm (1800 to 3000 rpm) and torque (75 to 125 lb-ft).

Figure D-3 is a map of the "Motor Voltage for a Nominal Design." Motor voltage is constant volts/cycle up to the corner point. From the corner point to the maximum speed, the motor voltage V varies as $Vo \times S^{\varepsilon}$, where:

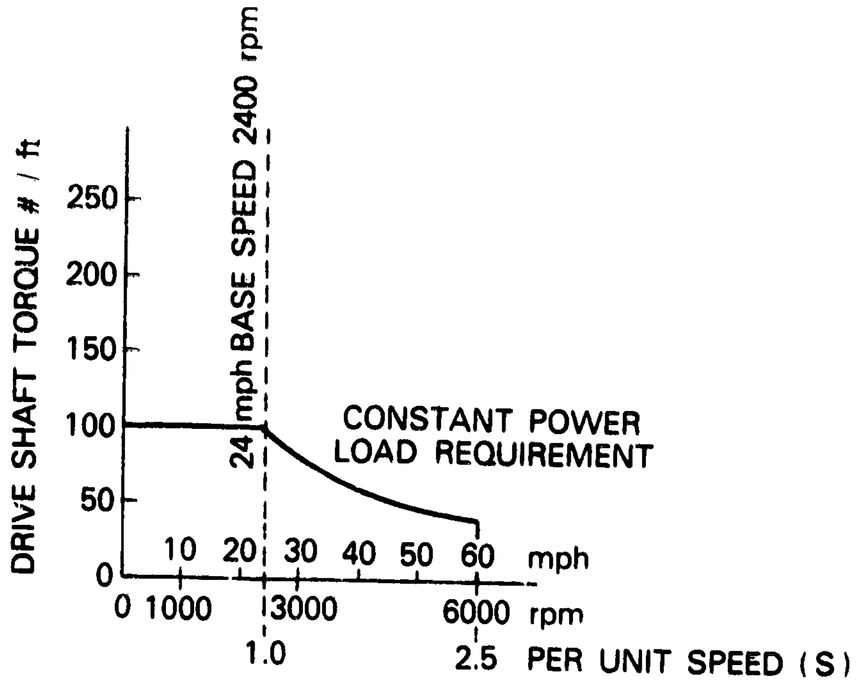


Figure D-1. Maximum Drive Shaft Torque Specification for a Nominal Design Motor

- Vo is the corner point voltage ($0.632 \leq V_o \leq 1.0$)
- S is the pu speed or pu rpm
- ε is an exponent ($0 \leq \varepsilon \leq 0.5$)

At maximum speed, N_{MAX} and S_{MAX}, the motor voltage is the highest ac voltage attainable when using a battery. It is designated V_{MAX} for convenience. It is assumed that power conditioner kVA is proportional to current and motor torque is proportional to D^2L or weight. These assumptions are satisfactory for small pertubations. When given T_{MAX}, No, and S_{MAX}, the lowest subsystem motor-controller cost occurs for the condition:

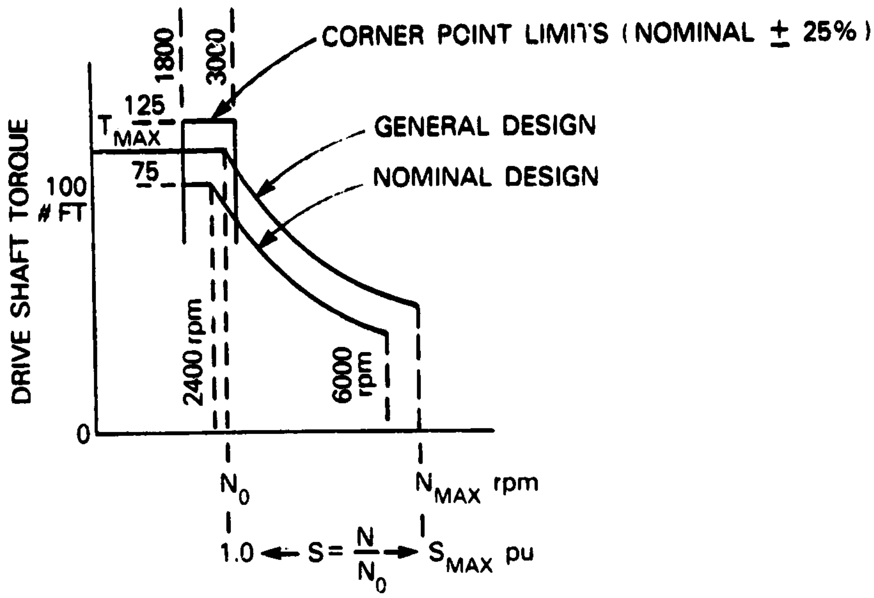


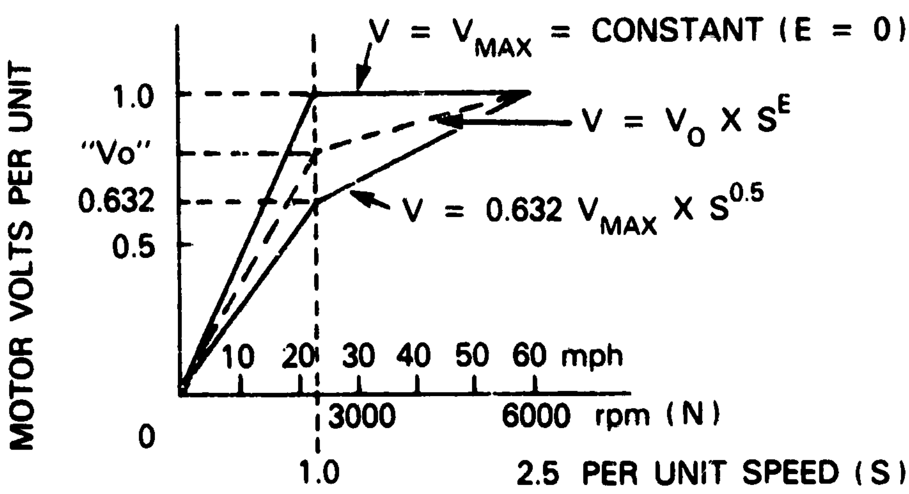
Figure D-2. General Specification for D.S. Torque

$$\frac{V_{MAX}}{Vo} = \sqrt[3]{2 \times \frac{M_c}{PC_c} S_{MAX}}$$

where:

M_c = motor cost for a corner point voltage V_o = 0.632

PC_c = power conditioner cost for a corner point voltage of V_o = 1.0.



MOTOR VOLTAGE FOR NOMINAL DESIGN

Figure D-3. Motor Voltage for Nominal Design

The exponent is:

$$E = \frac{\ln \frac{V_{MAX}}{Vo}}{\ln S_{MAX}}$$

The limits of $\frac{M_c}{PC_c}$ in the above equation are:

$$\frac{S_{MAX}^{0.5}}{2} \geq \frac{M_c}{PC_c} \geq \frac{1}{2\ S_{MAX}}$$

Results outside these limits must be evaluated on their own merits.

The power conditioner kVA is:

$$kVA_{PC} = \left[K_1 \times \left(\frac{T_{MAX}}{100} \times \frac{No}{2400} \right) \right] \times S_{MAX}^{\epsilon}$$

Corner Point (T_{MAX} = 100 lb/ft, No = 2400 rpm);

$$\text{DS Load} = \frac{2\pi \times 100 \times 2400}{33000} \times 0.746 = 45.7 \text{ kW}$$

$$K_1 \text{ (Input to Motor)} = \frac{\text{DS Load}}{\eta_T \times \eta_M \times \text{power factor}}$$

$$K_1 = \frac{45.7}{\underset{\eta_T}{\underset{\uparrow}{1.0}} \times \underset{\eta_M}{\underset{\uparrow}{0.88}} \times \underset{\text{power factor}}{\underset{\uparrow}{0.83}}} = 62\text{kVA}$$

Motor weight is:

$$\text{Motor Wt (lb)} = K_2 \times \frac{T_{MAX}}{100} \times S_{MAX}^{1-2\epsilon}$$

$$\text{Motor Air Gap Torque} = \frac{\text{Drive Shaft Torque}}{\eta_T \times K_\alpha}$$

Assume transmission efficiency (η_T) = 0.90

and Air Gap Torque = Motor Shaft Torque

or K_2 (Inertia Veh./Inertia System) = 1.0

K_2 might be as low as 0.85. This will be modeled later as a variable.

When we assume η_T = 0.9, the value of K_1 becomes 62. The value of K_2 is taken from a table and is 138.

Total cost and weight of motor-controller subsystem:

$$\text{Total Cost} = \text{kVA}_{PC} \times \left(\frac{\$}{\text{kVA}}\right) + \text{Motor Weight} \times \left(\frac{\$}{\text{lbs}}\right)$$

$$\text{Total Weight} = \text{kVA}_{PC} \times \left(\frac{\text{lbs}}{\text{kVA}}\right) + \text{Motor Weight}$$

A. MOTOR EVALUATION

If the motor shaft is direct connected to the transmission, the motor cost/lb is:

$$\left(\frac{\$}{\text{lb}}\right)_M = 1.8 \times \left(\frac{\text{No}}{1800}\right)^{0.5} \times \left(\frac{S_{MAX}}{2.5}\right)^{0.5}$$

$$\text{Motor Weight (lb)} = \left[138 \times \left(\frac{T_{MAX}}{100}\right)\right] \times S_{MAX}^{\,1-2^{\epsilon}}$$

$$\text{Motor Cost (\$)} = \text{Motor Weight (lb)} \times \left(\frac{\$}{\text{lb}}\right)_M$$

If the motor has an internal step down gear like a gearmotor with a ratio of r, the motor estimated cost per pound is:

$$\frac{\$}{\text{lb}}_{M} = 1.8 \times \frac{\text{No}}{1800}^{0.5} \times \frac{S_{MAX}}{2.5}^{0.5} \times r^{1.5}$$

$$= 1.8 \times \sqrt{\frac{\text{No}\ r^3\ S_{MAX}}{4500}}$$

where No is the rpm of the shaft which connects the gearmotor with the transmission.

$$\text{Motor weight for an aluminum gearmotor (lb)} = \left[\left(\frac{138}{r}\right) \times \left(\frac{T_{MAX}}{100}\right)\right] \times S_{MAX}^{\,1-2^{\epsilon}}$$

Again: $\text{Motor Cost (\$)} = \text{Motor Weight (lb)} \times \left(\frac{\$}{\text{lb}}\right)_M$

The lowest cost system will favor the more expensive controller. Therefore, the motor will be heavy. Weight may be reduced by using a gear motor (or its equivalent). However, motor shaft torque-to-inertia diminishes directly with r. Self-accelerating torque will be an important consideration for the final design.

Surface speed of the rotor which is related to rotational stresses has been ignored in the mathematics model.

Motor envelope dimensions are calculated using a volume density of 13.5 in.^{3} per pound and an overall length-to-diameter of 1.45. A blower is needed to cool the motor, but blower dimensions and mounting are not included in this envelope. Gears for a gearmotor have not been sized.

Efficiency at the corner point will be 87 to 91%. Efficiency over the duty cycle may be calculated from its equivalent circuit. Typical data might be used until the final design is started.

B. SUMMARY STATEMENT

These equations and their constants will enable the designer to focus on a design which should be just short of a final design. All equations and their constants should then be re-evaluated using new empirical data. This will minimize the uncertainty of the results by shortening the sealing range.

C. EMPIRICAL DATA

Reference Motor -- T/C 700 Aluminum Motor; Open 4-Pole

- Horse power = 20
- rpm = 1755
- T_{MAX} = 2.0 pu = 2 x 59.9 lb/ft
- Efficiency = 86 to 88%
- Power factor = 80 to 83%
- Weight = 149 lb
- Inertia = 1.91 lb/ft

Reference Motor -- High-Efficiency Design; Open 4-Pole

- Horse power = 20
- rpm = 1760 @ 60 Hz
- T_{MAX} = 2.0 pu = 2 x 59.7
- Efficiency = 0.92
- Power factor = 0.87
- Weight = 204 lb
- Inertia = 1.91 x 6/4.375 = 2.62 lb/ft

Reference Motor -- NASA Induction Motor; No gears

- Continuous horsepower = 22 @ 42V per phase
- rpm = 5370 @ 180 Hz
- Torque (J1=900)* = 65.2 lb/ft @ 45 V/pH
- Efficiency = 94.6 @ 22 hp
- Power factor = 69.4 @ 22 hp
- Weight = 90 lb
- Inertia = 0.55 lb/ft^2

Note: Calculated performance characteristics are speculative.

*The Maximum Torque of Motor is 122 lb/ft at a slip of 4.5% with 45 V/pH and 1040 A. This is not a cost-effective operating point because current is disproportionally high or torque-per-ampere is low.

$$(\$/lb)_{Motor} = A \times \sqrt{\frac{No\ S_{MAX}\ r^3}{4500}}$$

$$\text{Motor Weight alone (lb)} = \left[\left(\frac{B}{r}\right) \times \left(\frac{T_{MAX}}{100}\right)\right] \times S_{MAX}^{\ 1-2^{\varepsilon}}$$

	A	K_2 B	r
Aluminum motor	1.8	138	1
High efficiency	1.9	182	1
NASA induction motor	2.0	138	r

Note: Each succeeding motor type requires more development.

D. BACKGROUND FOR K_2

Torque per ampere degrades approaching T_{MAX}. So: Operate to only 90% of T_{MAX}.

Reference motor has a useful T_{MAX} = 0.90 x 2 x 59.9 lb/ft.
DS Load is specified as T_{MAX} = 100 lb/ft. Motor Shaft Load = $100/\eta_T$.
Assume Torque $\approx$ D^2L $\approx$ Weight

The weight of a motor that will produce a useful 100 lb/ft is:

$$\text{Weight} = 149 \times \frac{100/\eta_T}{107.8} = 138 \text{ lb}$$

$$\eta_T = 1.0$$

E. METHODOLOGY

The following material and calculations are presented to show methodology only and also to serve as a sample calculation.

Sample calculation for nominal design

T_{MAX} = 100; N_o = 2400; S_{MAX} = 2.5; Let r = 1.0

Corner Point Calculations for Optimum Power Conditioner

$$(V_o = V_{BAT};\ \underline{\varepsilon = 0})$$

From F.G.T. 1/20/79, p. 14A:

If $M = $37.50

62 kVA power conditioner will

weigh 1.4 lbs/kVA

cost $11/kVA or $\dfrac{\$682}{V_o=V_{BAT}} = PC_c$

Corner Point Calculations for Optimum Motor:

$$(V_o = 0.632\ V_{BAT};\ \underline{\varepsilon = 0.5})$$

$$\text{Motor Weight (lb)} = \left[138 \times \left(\frac{T_{MAX}}{100}\right)\right] \times S_{MAX}^{\ 1-2^{\varepsilon}}$$

$$= 138 \text{ lb}$$

$$\text{Motor \$/lb} = 1.8 \left(\frac{N_o}{1800}\right)^{0.5} \times \left(\frac{S_{MAX}}{2.5}\right)^{0.5}$$

$$= \$2.0785/\text{lb}$$

$$\text{Motor Cost } (M_c) = 138 \times 2.0785$$

$$= \frac{\$286.83}{V_o = 0.632\ V_{BAT}}$$

F. LOWEST COST SUBSYSTEM

$$\frac{M_C}{PC_C} = \frac{286.83}{682} = 0.4706$$

$$\text{Lowest Cost } \frac{V_{BAT}}{Vo} = \sqrt[3]{2 \times \frac{Mc}{PC_C} \times S_{MAX}}$$

$$= 1.28116 \quad \text{or} \quad \frac{Vo}{V_{BAT}} = 0.7805$$

$$\& \ \varepsilon = \frac{\ln \frac{V_{BAT}}{Vo}}{\ln S_{MAX}} = 0.2704$$

$$\text{PC-kVA} = \left[62 \times \left(\frac{100}{100} \times \frac{2400}{2400}\right)\right] \times 2.5^{0.2704}$$

$$= 79.43$$

$$\text{Motor Weight (lb)} = \left[138 \times \left(\frac{100}{100}\right)\right] \times 2.5^{1-2 \times .2704}$$

$$= 210.19 \text{ lb}$$

$$\text{Total Cost} = \text{PC-kVA} \times \left(\frac{\text{lb}}{\text{kVA}}\right) + \text{Motor Weight} \times \left(\frac{\$}{\text{lb}}\right)$$

$$= 79.43 \times 11 + 210.19 \times 2.0785 = \underline{\$1311}$$

$$\text{Subsystem Weight} = \text{PC-kVA} \left(\frac{\text{lb}}{\text{kVA}}\right) + \text{Motor Weight}$$

$$= 79.43 \times 1.4 + 210.19 = 321 \text{ lb}$$

G. HIGH MODULE COST

If $\$M = \$150$

$PC_C = 11.25 \times (\$M) + 250 = \$1937$

$\$5/kVA = \dfrac{1937}{62} = \$31.25$

$$\frac{M_L}{PC_L} = \frac{286.83}{1937} = 0.14808 \ngtr \frac{1}{2} \times S_{MAX}$$

Therefore: Let $V_O = V_{BAT}$ & $\varepsilon = 0$

and PC - kVA = 62

also Motor Weight (lb) $138 \times \dfrac{100}{100} \times 2.5^{1-2\times\theta} = 345$

Subsystem Cost $= \$1937 + \text{Motor Weight} \times \$/\text{lb}$

$= 1937 + 345 \times 2.0785 = \$2654$

Subsystem Weight $= 62 \times 1.4 + 345 = 431.8$ lb

Note: $K_\alpha \approx 1 - .0214 \times \left(\dfrac{345}{138}\right)^{5/3} = 0.90$

Again, for $\$M = 150$; assume a gear motor with $r = 2.5$ and assume motor power factor and efficiency unchanged (but actually that would not be the case).

Then,

Motor Weight $= \dfrac{345}{r} = \dfrac{345}{2.5} = 142$ lb

$$(\$/\text{lb})_{Motor} = 1.8 \times \left(\frac{N_o}{1800}\right)^{0.5} \times \left(\frac{S_{MAX}}{2.5}\right)^{0.5} \times r^{1.5}$$

$$= 1.8 \times \left(\frac{2400}{1800}\right)^{0.5} \times \left(\frac{2.5}{2.5}\right)^{0.5} \times 2.5^{1.5}$$

$$= \$8.216/\text{lb}$$

$$\text{Motor Cost} = 142 \times \$8.216 = \$1166$$

$$\text{Subsystem Cost} = \$1937 + 1166 = \$3103$$

$$\text{Subsystem Weight} = 86 + 142 = 228 \text{ lb}$$

$$\text{Note:}\quad K_\alpha = 1 - .0214 \times \frac{345}{138}^{3} \times 2.5^{1/3} = 0.86$$

The Inertia Ratio for 138-lb motor is 0.0214.

$$K_\alpha = 1 - 0.0214 \times \frac{\text{Wt Motor}}{138}^{5/3} \times r^{1/3}$$

$$= 1 - 0.0214 \times \frac{138 \times \frac{T_{MAX}}{100} \times S_{MAX}^{1-2^{\varepsilon}}}{138}^{5/3} \times r^{1/3}$$

$$K_\alpha = 1 - 0.0214 \times \frac{T_{MAX}}{100} \times S_{MAX}^{1-2^{\varepsilon}\ 5/3} \times r^{1/3}$$

Rather than use the gearmotor try a less optimum V_O/V_{BAT}. For PC = 1.4 lb/kVA; \$M = 150; \$/kVA = 31.25. Motor cost is \$2.0785/lb. One can then construct the following table.

V_O/V_{BAT}		PC-kVA	Motor Weight (lb)	Cost Subsystem (\$)	Weight Subsystem (lb)	K_α
1.0	0	62.0	345	2654	431	0.90
0.9	0.1150	68.9	279.4	2733	375	--
0.8	0.2435	77.5	220.8	2880	329	--
0.7	0.3893	88.6	169.1	3120	293	--
0.632	0.500	98.0	138.0	3350	275	0.98

No Gearmotor: \$3350 : 0.98 \$3418

Gearmotor : \$3103 : 0.86 \$3608

III. AC MOTOR DATA

Specific data defining the characteristics of an ac induction motor was needed as identified by the internal memorandum which follows. This data was furnished for use on the program in the form of a General Electric Company proprietary computer program devised by the Small AC Motor Department. The data is given in General Electric Company Brochure GEP-1087D, AC Motor Buyers' Guide, and in Table D-1.

Table D-1

AC MOTOR DATA

Continuous Duty Rating, hp	20.00
Base Speed (60 Hz), rpm	1800.00
Voltage per phase (LN), V	266.00
Line Current, A	23.32
Power Factor	0.87
Slip	0.0297
Stator Resistance (per phase at 95 $^{\circ}$C), ohms	0.3322
Rotor Resistance (per Phase Referred to Stator), ohms	0.2466
Stator reactance, ohms	1.159
Rotor Reactance per Phase Referred to Stator), ohms	1.184
Magnetizing Reactance (per phase referred to stator), ohms	42.45
Magnetizing Branch Resistance (in Series with Reactance), ohms	1.467

GENERAL ELECTRIC
CORPORATE RESEARCH AND DEVELOPMENT

P. O. BOX 43
SCHENECTADY, N. Y. 12301
DIAL COMM 8*235-

TO: MEMO FOR THE RECORD

FROM: C.B. Somuah

DATE: March 14, 1979

SUBJECT: TEST DATA ON AC INDUCTION MOTOR

As part of the Hybrid Vehicle Simulation studies, characteristics of ac induction motors in the horsepower range of 18 - 25 are required. The following list gives the specifications for the motor and also the type of test data required. The data is required for the computation of the winding resistances, leakage reactances, and the motor friction, windage and core losses. Alternatively, if these parameters are already available from test data or computer calculations, then they can be supplied instead of the test data.

MOTOR SPECIFICATIONS (3 Phase)

Continuous Duty	=	18 - 25 hp at 1800 rpm
Peak Power (20 sec.)	=	2 x continuous duty
Voltage Rating (L-L)	=	80 - 250 volts rms

REQUIRED TEST DATA

(1) No Load (Light Running) Test

- Power versus voltage
- Current versus voltage
- Power factor versus voltage
- Slip versus voltage

(2) Short Circuit (Locked Rotor) Test

- Power versus current
- Power factor versus current
- Voltage versus current

C.B. Somuah

C.B.S.

/dll
cc: A. Burke
R. Guess

II. SUMMARY OF AC POWER CONDITIONER STUDY

The ac power conditioner study resulted in the development of parametric equations, related to a specific duty cycle, for:

- Weight
- Volume
- Efficiency
- Losses
- Cost
- Component requirements

In addition, the effect of battery voltage level was examined and a comparison was made with other power conditioning systems.

1. $$I_{dc} = \frac{(\text{peak motor kVA})(\text{power factor of motor})(10^3)}{(0.95)(\text{battery voltage})} \text{ A}$$

2. Maximum fundamental frequency

$$= \frac{(\text{maximum motor speed})(\text{number of motor poles})}{120} \text{ Hz}$$

3. Maximum chopping frequency

$= (9)\ (f)/\text{speed ratio at constant power Hz}$

9 = chopping frequency ratio

4. rms kVA over duty cycle
(proportional to amperes)

5. $$\text{Weight} = 88 \left(\frac{I_{ac}}{483}\right) \left(\frac{\text{rms kVA over duty cycle}}{42.23}\right) \text{ lb}$$

6. Volume $= 2\left(\frac{I_{dc}}{483}\right)\left(\frac{\text{rms kVA over duty cycle}}{42.23}\right) \text{ ft}^3$

7. Power conditioner losses $= 100 + 1952\left(\frac{I_{dc}}{483}\right) + 54\left(\frac{I_{dc}}{483}\right)^2 +$

(constant power region) $3.5\left(\frac{I_{dc}}{483}\right)\left(\frac{f}{200}\right) + 140\left(\frac{I_{dc}}{483}\right)^2\left(\frac{f}{200}\right) \text{ W}$

8. Power conduction losses $= 100 + 1952\left(\frac{I_{dc}}{483}\right) + 54\left(\frac{I_{dc}}{483}\right)^2 +$

(constant torque region) $+ 50\left(\frac{I_{dc}}{483}\right)\left(\frac{f_{chop}}{720}\right) +$

$504\left(\frac{I_{dc}}{483}\right)^2\left(\frac{f_{chop}}{720}\right) \text{ W}$

9. Efficiency $= 100\left[\frac{E_{BATT} \cdot I_{dc} - P_{losses}}{E_{BATT} \cdot I_{dc}}\right] \%$

10. Power conditioner cost = 11.25 (\$M)+\$250, \$M = power transistor module cost

11. Power conditioner cost/kVA peak = [11.25(\$M)+250]/62

if \$M = 37.50, then $\frac{\text{cost}}{\text{kVA}}$ = 11 \$/kVA peak

12. PCU weight/kVA = 1.4 lb/kVA peak

13. PCU Volume/kVA peak = 0.003 ft^3/kVA peak

14. Battery voltage level. In order to reduce weight, volume, and cost and increase efficiency, one may increase battery voltage to the limits imposed by power transistor switching voltage ratings.

E_{BATT} max = 150 for regenerative systems
E_{BATT} max 216 for nonregenerative systems

Based on V_{CEO} (SUS) rating of 450 V.

15. Comparison with other ac systems. For the present study, the National Aeronautics and Space Agency ac Controller and Rohr 312 are equivalent except the weight of the Rohr 312 may not include dc capacitors or a dc contactor.

A. DESIGN EQUATIONS FOR AC POWER CONDITIONING STUDY

Based on engineering calculations, the rating of the power conditioner is 62 kVA at the corner point.

For a six-step waveform, the line-to-neutral ac voltage is equal to 0.45 (E Battery)

$$e_{L-N} = 0.45(108) = 48.6 \text{ V}$$

$$I_{rms} = \frac{62,000}{3(48.6)} = 425 \text{ A rms}$$

$$\text{ac Power} = \text{kVA} \cdot \text{power factor}$$

$$= 62,000\ (0.8) = 49,600 \text{ W}$$

$$\begin{array}{l}\text{dc Current} \\ \text{(average)}\end{array} = \frac{\text{ac power}}{(\text{Eff pcu})(E_{BATT})} = \frac{49,600}{\underset{\text{assumed}}{(0.95)}(108)} = 483 \text{ A}$$

$$i \text{ Peak Transistor} = I_{rms}\ [\sqrt{2} + (\text{harmonic component})]$$

$$= 425\ [\sqrt{2} + (1.76\text{x}10^{+3})(1.37\text{x}10^{-4})(2.26)]$$

$$= 425\ (\sqrt{2} + 0.545) = 425\ (1.959)$$

$$= 832 \text{ A}$$

The circuit diagram is given in Figure D-4.

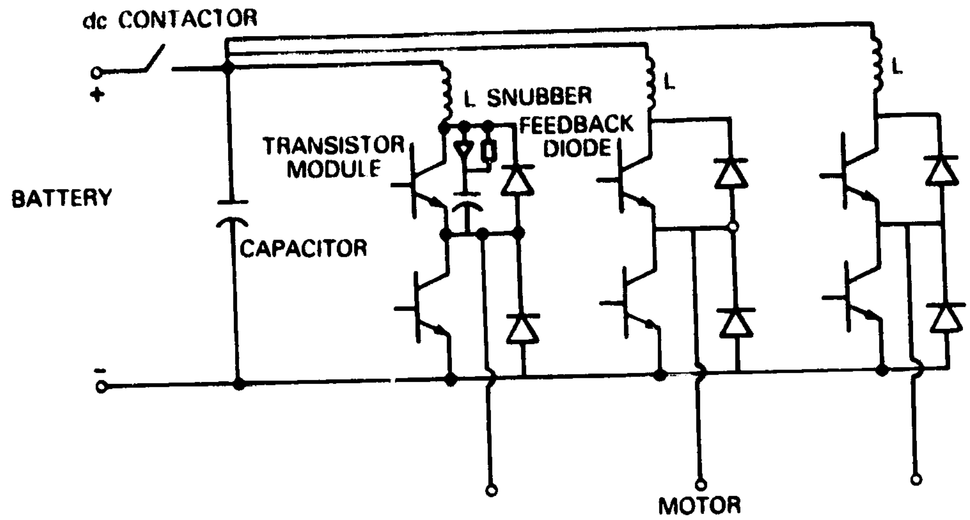


Figure D-4. Power Circuit Diagram

Power Conditioner Losses at Maximum Frequency

Assume battery cable inductance (L) = 2 μh

1. Commutation loss (no recovery)

$$P = \frac{1}{2}\, LI^2\, f = \frac{1}{2}(2)(10^{-6})(483)^2(200)$$

P = 46.6 W/phase = 140 W total
in square wave at maximum frequency

2. Transistor and feedback diode correlation loss

$$P = \begin{pmatrix} E_{ON} \\ \text{TRANS} \end{pmatrix} \left(I_{AVE}\right) \begin{pmatrix} \text{Ratio of} \\ \text{on time} \end{pmatrix} + \begin{pmatrix} E_{ON} \\ \text{Diode} \end{pmatrix} \left(I_{AVE}\right) \begin{pmatrix} \text{Ratio of} \\ \text{on time} \end{pmatrix}$$

$$P = (1.8)\left(\frac{483}{3}\right)\left(\frac{2}{3}\right) + (2.4)\left(\frac{483}{3}\right)\left(\frac{1}{3}\right)$$

P = 322 W device

P_{TOTAL} = 6 x 322.5 = 1932 W

3. Transistor switching loss

$$P = I_{AVE} E_{dc} \frac{t_{fall}}{t_{period}}$$

$$P = \frac{483}{3} (108) \frac{2 \times 10^{-6}}{2500 \times 10^{-6}}$$ at 200 Hz, t_{period} equals 2500 μs

$P = 3.5$ W

4. Total losses

Transistor & diode loss = 140 + 1932 + 3.5 = 2076 W
(square wave at 200 Hz)

<u>Power Conditioner Losses at Maximum Chopping Frequency</u>

In the PWM mode maximum frequency of chopping is

$$200 \underbrace{\frac{1}{2.5}}_{\text{speed ratio}} \times 9 = 720 \text{ Hz}$$

1. Commutation loss

$$P = 3 \frac{1}{2} (L)(I^2)(f)$$

$$= (3) \frac{1}{2} (2)(10^{-6})(483)^2(720)$$

$$= 504 \text{ W}$$

2. Conduction loss = same = 1932 W

3. Switching loss

$$P = \frac{483}{3} (108) \frac{2 \times 10^{-6}}{694 \times 10^{-6}}$$ at 720 Hz, period is equal to 694 μs

$P = 50.1$ W

4. Total losses in transistor & diode (at 9 x f below corner point) = 504 + 1932 + 50 = 2486 W

<u>Additional Losses in AC Power Conditioner</u>

1. Base drive loss $= \frac{I_C}{100} \times V_{BE}$ gain of Darlington

$$= \frac{483}{100} \times 4 = 20 \text{ W}$$

2. Control power = 100 W (assumed)

3. Capacitor loss $= I^2R$

I harmonic $= (425(0.545))^2$

$P = (425)^2 (0.545)^2 (0.001) = 54$ W

Total System Efficiency

1. PCU efficiency (square wave at 100 Hz)

$$= \frac{(108)(483) - \overbrace{2075 - 20 - 100 - 54}^{2249}}{(108)(483)}$$

$= 95.7\%$

2. PCU efficiency (at 9f at 80 Hz fundamental)

$$= \frac{(108)(483) - \overbrace{2486 - 20 - 100 - 54}^{2660}}{(108)(483)}$$

$= 94.9\%$

The electrical design is for the peak instantaneous voltage, current, etc., corresponding to the 2.0 per unit torque requirement. The continuous rating of the system is one-half of the peak rating. Therefore, the continuous rating is 3/kVA.

The 2.0 torque from the duty cycle corresponds to 62 kVA, the 0.4 torque corresponds to 24.8 kVA. The rms kVA which is proportional to torque is as follows:

$$\text{rms kVA} = \frac{(62)^2(20) + (24.8)^2(20)}{50}$$

$$= 42.23 \text{ kVA}$$

The ratio of peak to rms kVA is 62/42.23 = 1.47 for the specified duty cycles.

In order to calculate the parametric equation relating weight to power conditioner electrical specifications, two factors are paramount. First, for those items that have no thermal storage capability, for example, power transistors and diodes, the weight will be proportional to the peak battery current. If the peak current is increased, additional components will be required leading to a direct increase in weight. Second, for these items that do have thermal storage capability (compared to the 20s 62 kVA specification), e.g., heat sinks, the weight will be proportional to the rms kVA over the duty cycle. For these components if the rms current is increased over the duty cycle, there will be a direct increase in the system weight. Therefore, the weight equation will be composed of three items: first, a constant of proportionality; second, a term proportional to peak dc current; and third, a term proportional to rms kVA over the duty cycle.

$$\text{Weight} = K_1 \quad \frac{I_{dc}}{483} \quad \frac{\text{rms kVA over duty cycle}}{42.23}$$

In order to determine K, one needs to calculate the weight of the 31-kVA, 108-V design.

Component and Heat-Sink Weight

1. A representative heat sink for power transistors would be a Wakefield 132-4.5. It has a thermal resistance of 0.15 °C per watt and a one-minute thermal time constant. Its weight (with a clamp) is 1800 g.
2. Solid-state device of current rating = 200 g independent of current rating
3. Snubber = 200 g
4. Driver electronics = 200 g

   Total electronics 2400 g ≈ 5 lb
5. dc Contactor ≈ 3.75 lb
6. Control circuits and microprocessor ≈ 5 lb
7. dc Capacitors ≈ 20 lb

Total Weight of AC Propulsion System

	Unit Weight (lb)	Total Weight (lb)
6 Transistor/Diode Modules	5.00	30.00
1 Control Circuit	5.00	5.00
1 dc Contactor	3.75	3.75
1 Capacitor	20.00	20.00
Subtotal		58.75
Package Weight assuming it is 50% of total		29.38
Total Weight		88 lb

Weight Equation

Weight = 88 $\frac{I_{dc}}{483}$ $\frac{\text{rms kVA over duty cycle}}{42.23}$ lb. Based on this equation, several conclusions can be reached:

1. Effect of battery voltage - If battery voltage increases, dc current decreases and weight is decreased.
2. Effect of ϵ exponent in voltage corner point equation - As ϵ increases, from zero to 0.5 the corner point current increases, thereby increasing the weight directly, as shown in Figure D-5.

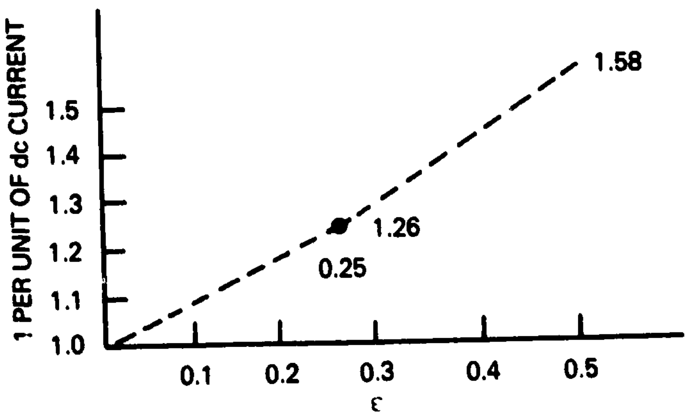


Figure D-5. Effect of ϵ Exponent in Voltage Corner Point Equation

Power Conditioner Size

Size is again proportional to the weight, and the same factors that influence weight influence size. Assume that size if related to continuous kVA. The present dc power conditioner is 1.60 ft^3 and weighs 95 lb. It has a one-minute rating of 48.6 kW and a continuous rating of 24.3 kV.

$$\text{Volume} = K_2 \frac{I_{oc}}{483} \frac{\text{rms kVA over duty cycle}}{42.23}$$

The calculation of the K_2 coefficient proceeds as follows.

$$\text{for the dc controller, } \frac{ft}{kW} = \frac{1.6}{24.3} = 0.0658\left(\frac{ft^3}{kW}\right)$$

$$\text{for the ac controller, } ft^3 = 0.0658\ (31) = 2.04$$

$$\text{Volume} = 2\ \frac{I_{dc}}{483}\left(\frac{\text{rms kVA over duty cycle}}{42.23}\right)ft^3$$

Dimensions are flexible, and a rectangular or cubic package is permissible. The thermal path for forced air will influence the shape.

Power Conditioner Losses

Use the equation in the form of $P = K_1 + K_2 I + K_3 I^2 + K_4 (\frac{f}{f_B})(I) + K_5 (\frac{f}{f_B})(I)^2$.

K_1 = loss that is not a function of current, i.e., control power, pins, base drive power etc.

K_2 = loss that is proportional to current, i.e., transistor with voltage drop independent of current.

K_3 = resistive loss, proportional to I^2.

K_4 = loss due to operation at higher frequency than base frequency (f_B of 200 Hz) to account for transistor switching loss increment.

K_5 = loss due to operation at a higher frequency than base frequency to account for additional resistive losses.

In the constant power mode of operation:

$$P_{Losses} = 100 + 1952\left(\frac{I}{483}\right) + 54\left(\frac{I}{483}\right)^2 + 3.5\left(\frac{I}{483}\right)\left(\frac{f}{200}\right) + 140\left(\frac{I}{483}\right)^2 \frac{f}{200}$$

In the constant torque mode of operation:

$$P_{Losses} = 100 + 1952\,\frac{I}{483} + 54\,\frac{I}{483}^{2}$$

$$+\ 50\,\frac{I}{483}\,\frac{f/chop}{720} + 504\,\frac{I}{483}^{2}\,\frac{f/chop}{720}$$

with f chop $= \frac{(9)(f)}{\text{speed ratio}}$.

Power Conditioner Efficiency

$$\text{Efficiency} = 100\,\frac{(E_{dc})(I_{dc}) - P_{Losses}}{E_{dc}I_{dc}}$$

$$= (100)\cdot\frac{(108)(483) - 2249}{(108)(483)} = 95.7$$

The part-load efficiency is calculated and plotted as follows.

(Figure D-6)

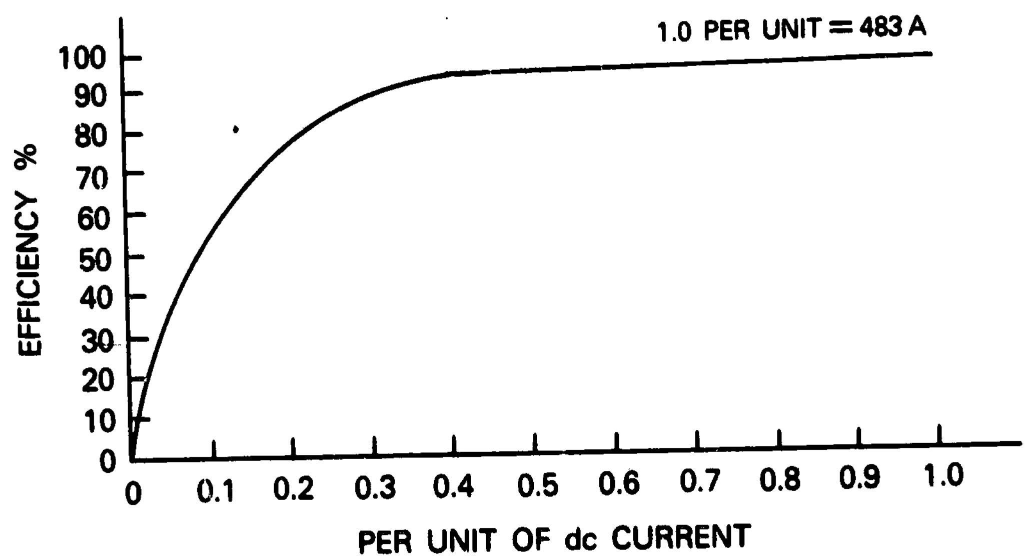


Figure D-6. Calculated Efficiency Versus per Unit dc Current

Cost of Power Conditioner

Major Component	Number in Circuit	($) Cost (ea)	($) Total Cost
1. Transistor & Diode Module	6	$M*	6($M)*
2. dc Capacitor	1	20	20
3. dc Contactor	1	10	10
4. Control Circuits	1	100	100

*Module cost ($M) will be a parameter in the cost equation.

The total cost of major components = 6($M) + 130 dollars.

Assuming that minor electrical parts add 25% to the total cost of major electrical parts, the total cost of all components = 125[6($M) + 130].

Assuming that packaging and assembly add 50% to the total cost of major and minor electrical parts, the total cost of equipment = 1.5[1.25(6($M) + 130)]. Collecting terms, results in:

Total cost of power conditioner = 11.25($M) + $250

The cost of a power module ($M) has been treated as a variable, the total cost as a function of the module cost is given in Figure D-7.

Cost/kVA Peak

$$\frac{\text{Cost of Power Conditioner}}{\text{kVA}} = \frac{(11.25)(\$M) + 250}{62} \quad \$/\text{kVA}$$

if $M = $37.50, then $/kVA = 11

if $M = $50., then $/kVA = 13

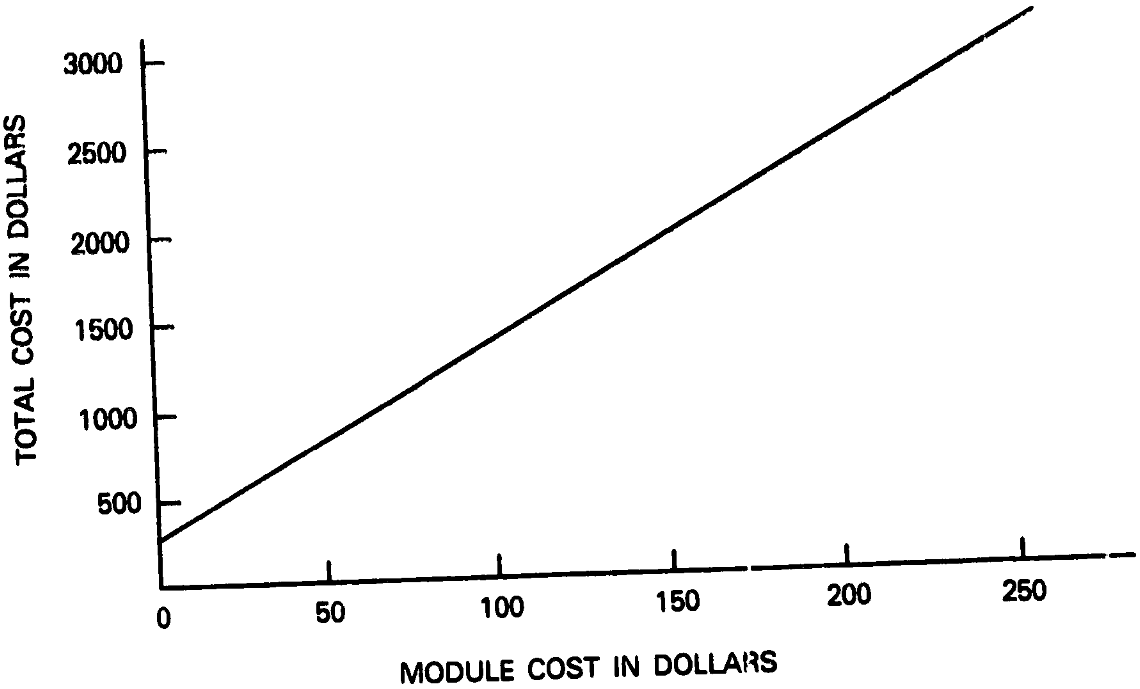


Figure D-7. Total Cost as a Function of Module Cost
If \$M = 37.50, then Total Cost = \$675
If \$M = 50.00, then Total Cost = \$825

<u>Weight/kVA Peak</u>

Weight/kVA = 88/62 = 1.4 lb/kVA peak constant over 25% range of variables.

<u>Weight/kVA Continuous</u>

Weight/kVA continuous = 88/31 2.8 lb/kVA continuous.

<u>Volume/kVA Peak</u>

Vol/kVA peak = 2.04/62 = 0.03 ft^3/kVA peak

B. EFFECT OF BATTERY VOLTAGE LEVEL

1. Factors That Would Favor an Increase in Battery Voltage

1. The conduction voltage $V_{CE(SAT)}$ of power transistors is independent of current and equal to 1.5-1.8 v for Darlington transistors, results in higher efficiency.

2. Less current means a smaller area of silicon for power transistors and diodes resulting in lower cost.

3. Less current means less transistor switching loss, resulting in higher efficiency.

4. Less current means less resistive loss (I^2R) in capacitors, cables, etc. which results in higher efficiency.

5. Less current permits smaller size of series reactive elements (if required), which results in smaller size.

6. Less current allows smaller cables resulting in a lighter weight vehicle.

2. Factors That Would Favor a Decrease in Battery Voltage

1. Transistor voltage rating (V_{CED} and V_{SUS}) during switching off should be limited to approximately one-half of the battery voltage. Since the present transistor V_{CED} rating is 450 v, maximum battery voltage equals 450/2 or 225 V dc. During regeneration, the battery voltage level will increase.

2. Low ESR electrolytic capacitors have dc voltage ratings less than 150 V. However, computer grade electrolytic (slightly higher ESR) capacitors have voltage ratings to 450 V.

3. Snubber loss is proportional to the square of the battery voltage $P = 1/2\ CE^2\ f$ or $1/2\ LI^2\ f$, results in slightly lower efficiency.

3. Summary

For maximum efficiency, lowest weight, and smaller size, increase dc voltage to the limit imposed by present power transistor switching voltage ratings; approximately 216 V for nonregenerative systems or 150 V for regenerative systems.

C. TRANSISTORIZED AC POWER TRANSISTOR

PROPULSION SYSTEMS COMPARISON

Parameter	Hybrid[1] Vehicle Study	Rohr[2] 312	NASA[3] ac Controller
Battery voltage, volts	108	96	108
kVA (maximum)	62	88	50
kW (maximum at .8 power factor)	50	70	40
Maximum fundamental frequency, Hz	200	300	500
Efficiency, %	95	92-97	94-97
Peak transistor current, A	827	-	680
Battery current, A	480	-	400
Approximate weight, lb	88	46[4]	87

[1] Present study calculations
[2] NASA CR-135340 April 1978
[3] Present contract calculations and progress reports
[4] Weight of contactor or dc capacitors may not be included in this total

Section 4 Attachment E

PRODUCIBILITY ANALYSIS

FOREWORD

A cost-reduced redesign for the Power Conditioning Unit (PCU) developed on the Near-Term Electric Vehicle Program - Phase II has been completed. The costs based on this methodology have been used in the detailed trade-off studies. The producibility analysis which was completed is presented here.

PRODUCIBILITY ANALYSIS OF ELECTRICAL DRIVE SUBSYSTEM FOR NEAR TERM ELECTRIC VEHICLE

Robert D. King

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HMED - Advanced Development Engineering
Syracuse, N.Y.

April 2, 1979

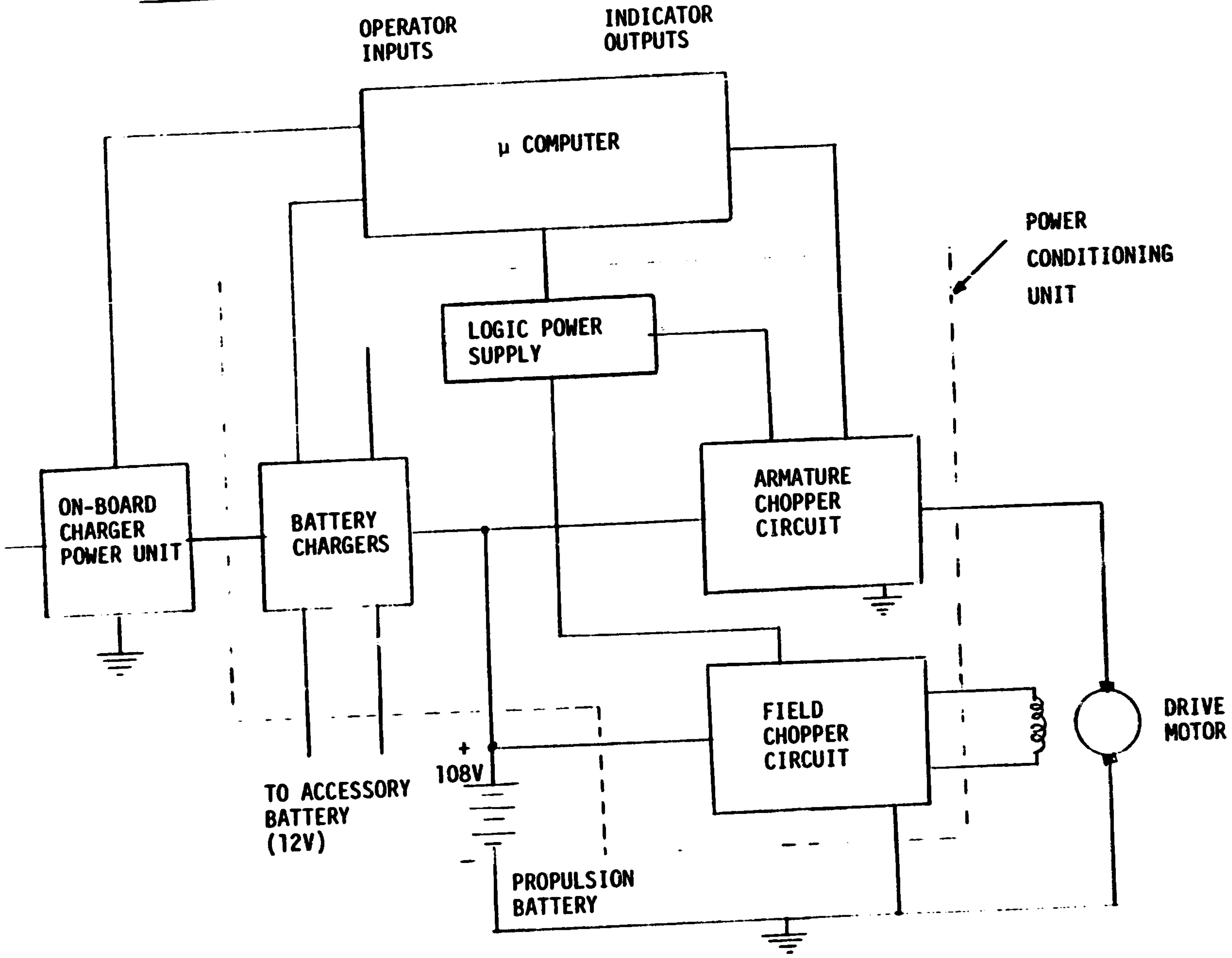
I. INTRODUCTION

This producibility analysis estimates the selling price of a production Electrical Drive Subsystem, EDSS, for the Near-Term Electric Vehicle. Results from this cost estimate will be integrated with the cost estimate of the vehicle, to be provided by Chrysler Corporation, to establish the selling price of a production version of the Near-Term Electric Vehicle. Production quantities of 100,000 electric vehicles per year starting in 1982, are assumed for this cost analysis.

Manufacturing cost, for this analysis, is defined as the sum of the material cost, material handling, labor (direct and indirect), and factory overhead. Acquisition (selling price) includes the manufacturing cost plus payback of investment for plant, equipment, research and development, and profit (after taxes). EDSS selling price does not include any cost of sales adders, since it is only a subsystem that will be integrated into the total vehicle.

Major components (using Integrated Test Vehicle, ITV, terminology) of the EDSS include: Microcomputer (μ computer), Power Conditioning Unit (PCU), electric drive motor, on-board charger power unit, and propulsion batteries. Additional EDSS components include: internal EDSS electrical interface, component temperature sensing and control, plus cooling fans. Figure 1-1 illustrates a functional block diagram of the major EDSS components and electrical interface. Operator interface with EDSS are all assumed to be elec-

FIGURE 1-1. ELECTRIC DRIVE SUBSYSTEM BLOCK DIAGRAM (ITV TERMINOLOGY)



trical; i.e., a voltage proportional to accelerator pedal position, brake differential pressure transducer, and logic levels corresponding to selector switch positions, etc. Conversely, EDSS provides electrical signals with sufficient power to drive indicator lights and the fuel gauge in the instrument panel.

Redesign and simplification of the ITV EDSS is necessary to achieve a low cost electrical drive subsystem for a high volume Production Electrical Vehicle (PEV). Producibility of the redesigned EDSS is improved via system simplification, Large Scale Integration (LSI), alternate packaging concepts, and high volume automated production/testing techniques.

EDSS producibility analysis manufacturing and selling price results presented in the report are appropriate only for the following assumptions:

1) Costs are in first quarter 1979 dollars

2) 100,000 EDSS systems (vehicles) are produced per year starting in 1982

3) Major plant and equipment investments are amortized over 10 years (1,000,000 vehicles)

4) R&D and production prototype programs are amortized over three years (300,000 vehicles)

5) Vehicle R&D and production prototype programs have been completed prior to 1982 production

6) Automated manufacturing and computerized testing techniques are used extensively to reduce production costs

7) Production Electric Vehicle, PEV, performance equal or superior to Integrated Test Vehicle, ITV

8) Drive motor cost based on a G02V index of 100 in General Electric's Apparatus Handbook

9) Drive motor length dimension and weight can be optimized for minimal EDSS system cost

10) EDSS cost optimization allows alternate component packaging techniques.

II. EDSS PRODUCIBILITY ANALYSIS RESULTS

Electric vehicle Electrical Drive System (EDSS) producibility analysis results presented in this section are appropriate only for the assumptions stated in Section I. Table 2-1 provides a functional summary of the estimated manufacturing cost of the EDSS. Material costs are obtained from vendor quotes/estimates of the components in production quantity. Labor estimates are based on typical assembly times for similar General Electric Electronic systems. Table 2-2 illustrates that the selling price estimate of a Production Electric Vehicle (PEV) EDSS is $2,697.89.

In this study, propulsion batteries and drive motor are obtained via subcontracts. These subcontracted items are assumed delivered directly to the vehicle manufacturer for installation. Therefore, no overhead adders or profits are attached to these subcontracted items.

The following section provides detail on the cost methodology, ITV simplification, and packaging techniques used in obtaining the PEV EDSS costs.

TABLE 2-1

EDSS FUNCTIONAL COST SUMMARY

FUNCTION	MATERIAL COST($)	LABOR (MINUTES)	EST. MFG. COST ($), 100K QTY.	
EV Integrated Control	38.88	27.6	73.58	
Battery Chargers & Logic Power Supply Brd.	106.03	119.4	233.72	PCU
PCU Backplane & Housing	9.11	29.7	34.66	
Armature/Field Base Drive Brd.	48.68	63.5	113.83	PU
Armature Chopper Pwr. Ckt.	218.26	23.8	314.68	
On-Baord Charger Pwr. Unit	58.49	18.0	93.05	
Battery Cable/ Connectors	16.40	4.0	25.30	
Misc. (Fan, Wiring, Sys. Test, etc.)	36.46	36.0	76.59	
PCU/PU/OBCPU Subtotal	$532.31	322.0 Min.	$965.41	
Propulsion Batteries/Connectors			693.00	
Drive Motor			820.00	
Total Manufacturing Cost			$2,478.41	
Equipment/Development Amortization			22.00	
TOTAL EDSS MANUFACTURING COST + R&D			$2,500.41	

TABLE 2-2

EDSS SELLING PRICE SUMMARY

	COST/UNIT ($)
EDSS Manufacturing Cost (less drive motor & propulsion batteries)	$965.41
Equipment/Development Amortization	22.00
Profit (10% after taxes)	197.48
Drive Motor (subcontract)	820.00
Propulsion Batteries (subcontract)	693.00
TOTAL EDSS SELLING PRICE	$2,697.89

III. ELECTRIC DRIVE SUBSYSTEM COST METHODOLOGY

Electric Drive Subsystem production cost reduction is achieved via system simplification, large scale integration (LSI), alternate packaging concepts, and high volume automated production/testing techniques. The following sections outline the methodology leading to cost models used for obtaining EDSS production cost estimates presented in Section II.

A. EDSS System Simplification

EDSS design and packaging of these units for the present Integrated Test Vehicle (ITV) are not conducive to low cost, high volume producibility. After reviewing the present ITV design, the following simplifications were assumed for the Production Electric Vehicle (PEV) cost models:

1) Separate the field chopper and 108 volt battery charger functions
2) Combine the 108 volt and accessory battery (12V) charger functions with redesigned circuitry
3) Expand the functions of the μ computer in the PEV
4) Simplify base drive functions via VMOS circuitry
5) Reduce the armature chopper rating via different drive motor
6) Simplify Logic Power Supply
7) Simplify on-board Charger Power Unit

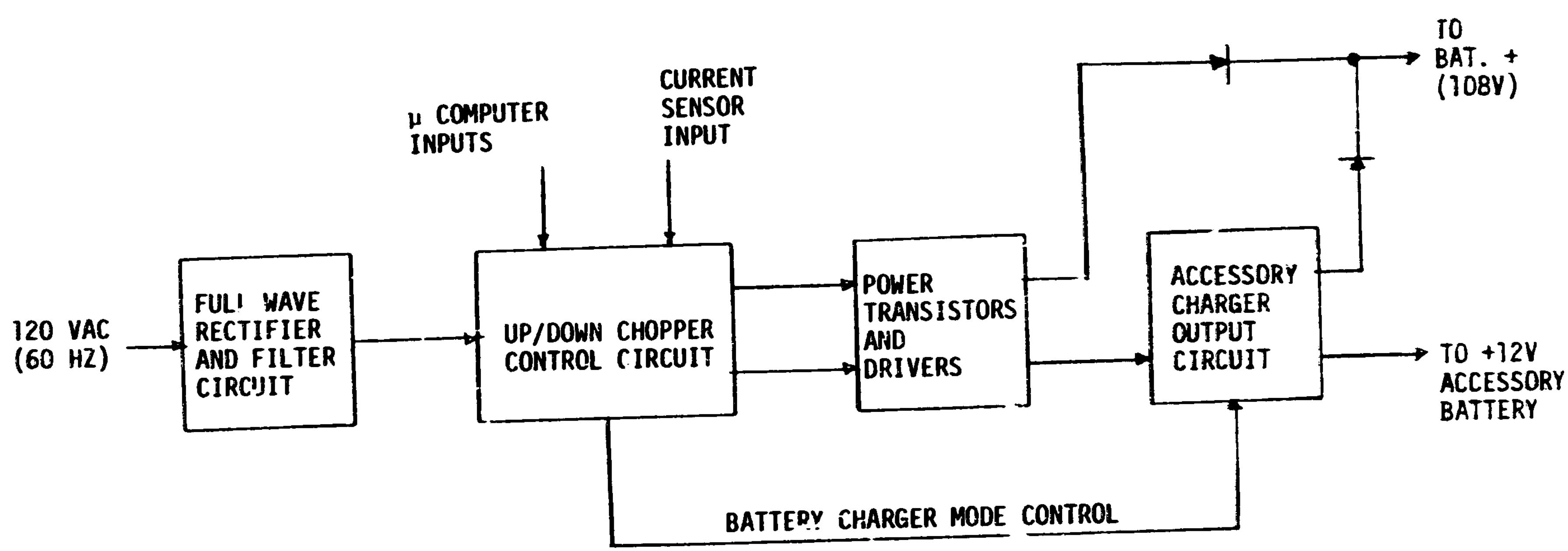
Separating the field chopper and the 108 volt battery charger functions simplifies control circuitry and utilizes lower cost power semiconductors.

The 108 volt battery charger for the PEV is an UP/DOWN chopper design that is controlled via the μ computer. Improved power factor and more efficient utilization of the battery charger power source results from this redesign concept. With the addition of a transformer and control system modifications, the 108 volt and 12 volt battery charger functions can be combined and, thus, reduce the battery charger costs by using common components. Figure 3-1 illustrates the combined battery charger block diagrams. This configuration assumes that the 12 volt accessory battery is charged and maintained at full charge from the 108 volt battery during normal driving. Input 120 VAC power is used only to charge the 108 volt battery bank.

Increasing the number of functions performed in the μ computer and dedicated digital interface circuitry reduces EDSS system costs. With rapidly declining costs of μ processors and μ computers, due to extremely high volume commercial, industrial, and automotive applications, expansion of μ computer functions to replace dedicated hardware reduces system costs.

Pulse Width Modulation (PWM) functions, including field chopper, armature chopper and fuel gauge in the PEV, are performed with dedicated digital circuitry under μ processor control. Since the desired output of the PWM circuitry is a one-bit digital signal; i.e., on or off, Digital to Analog (D/A) conversion is not necessary. Fuel gauge PWM output signal is low pass filtered in the analog fuel gauge. Therefore, the μ computer output interface

FIGURE 3-1. EV PATTERY CHARGER SUMMARY



in the PEV is simplified and all D/A converters used in the ITV have been eliminated. Figure 3-2 illustrates the μ computer block diagram with general inputs and outputs. The CPU portion of this μ computer requires from 3 to 6 IC's, depending on the configuration selected. Integrated packaging, discussed in greater detail below, significantly simplifies the input interface circuitry.

Simplified base drive circuitry for armature and field choppers reduce EDSS system costs for the PEV. Off-the-shelf VMOS power transistors provide the interface and power amplification between the logic level control signals and the power semiconductors. Optical isolation circuits plus isolated base drive power supplies achieves an efficient low noise, low volume implementation. Figures 3-3 and 3-4 illustrate the block diagram of the armature and field chopper with the VMOS interface between the control logic and power semiconductors.

Simplification of the armature chopper power circuit of the ITV is necessary to reduce the EDSS system cost. However, due to the relatively small number of high cost items, including high power semiconductors, capacitors and contactors, it is difficult to achieve the dramatic cost reduction necessary for the PEV in its present configuration. Two possible approaches to reducing costs include: utilization of a single higher current rated power module that is presently being developed, or select a different motor that is designed with a lower base speed which essentially halves the current rating of the armature chopper. The initial technique reduces the power

FIGURE 3-2. μ COMPUTER SUMMARY

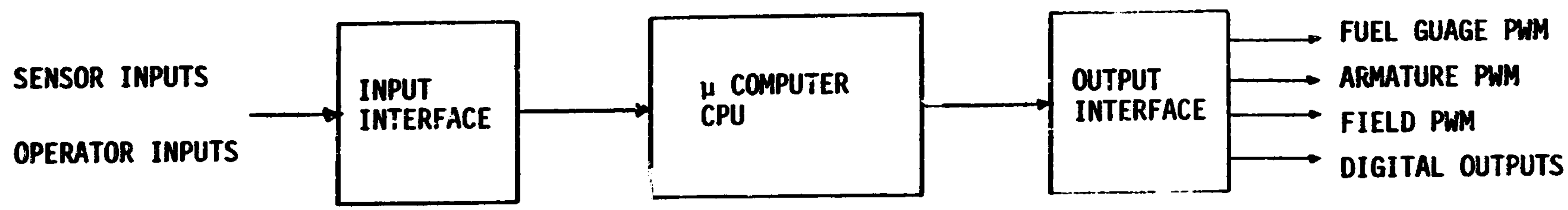


FIGURE 3-3. EV ARMATURE CHOPPER SUMMARY

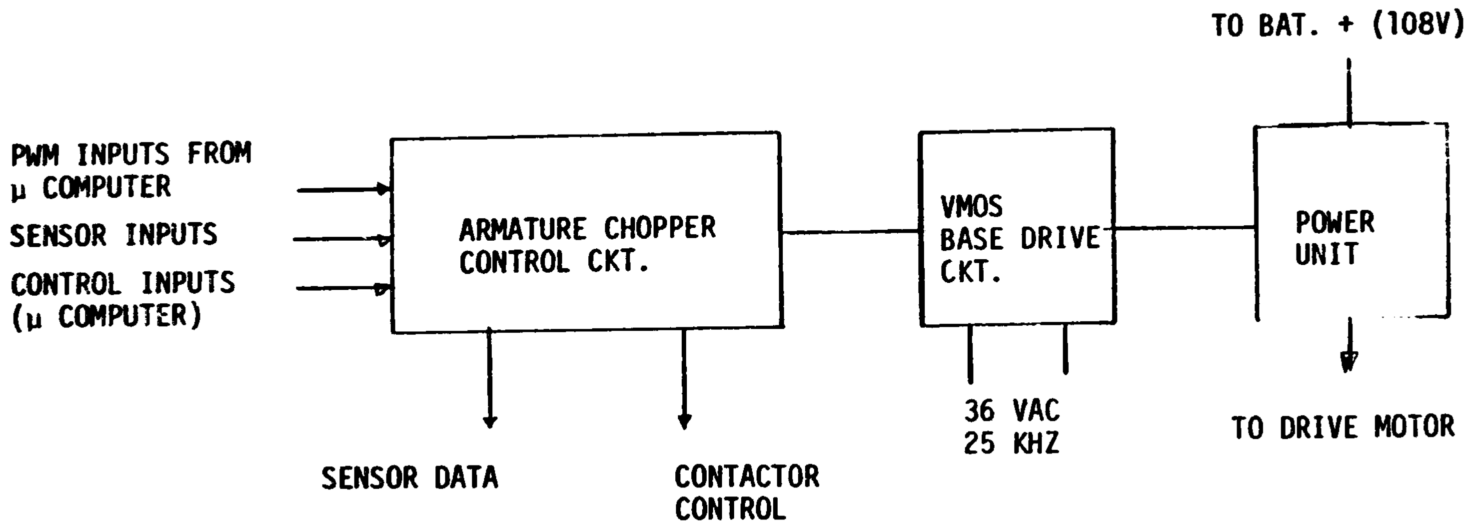
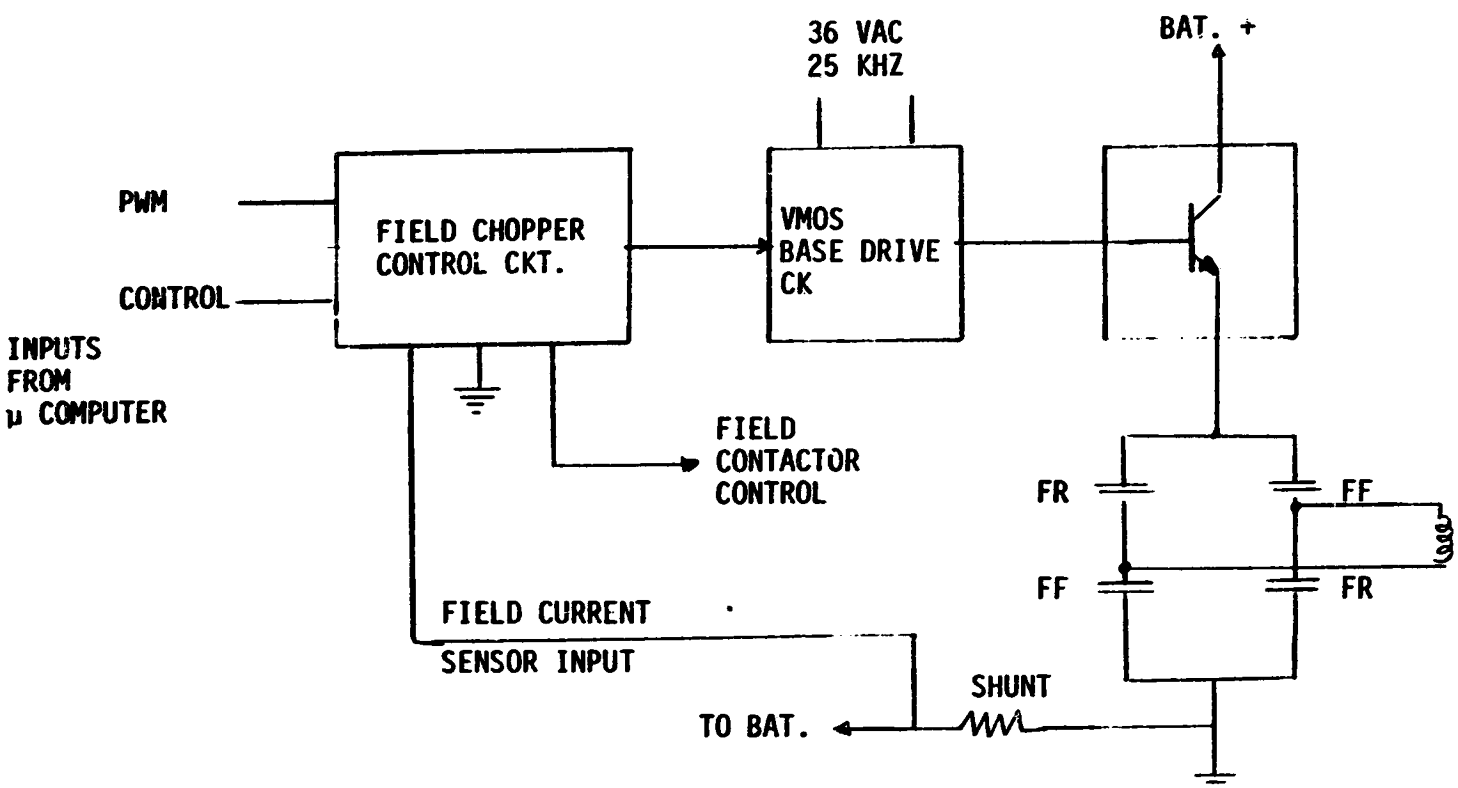


FIGURE 3-4. EV FIELD CHOPPER SUMMARY



semiconductor cost by 1/3, but no reduction in capacitor cost. The latter design provides increased torque per amp at lower speeds. Armature chopper bypass mode is utilized at a lower speed than the ITV design. In addition, this design concept is expected to increase gradability of the vehicle. Halving the current rating on the armature chopper includes: 1/3 power semiconductor, 1/2 rating of snubber circuit, and 1/2 rating on base drive circuit (3 amp instead of 6 amp base drive circuit). Disadvantages of this concept include: the required motor is physically larger, has increased weight, and is more costly than a production version of the ITV drive motor. Preliminary tradeoffs indicate a 1750/5000 RPM motor reduces PEV system cost and is the design assumed for this producibility analysis. However, future device development may warrant a reevaluation of this armature chopper/motor tradeoff.

Reduced logic power supply requirements, due to reduced μ computer and I/O power requirements, reduced base drive requirements, and low power integrated control circuits, allow a lower cost, reduced weight and smaller volume implementation. Three DC LPS outputs (+5V, ±15V), compared with the five required for ITV (+5V, ±15V, +12V) have estimated power requirements less than 20% of the ITV design. Using a 1750/5000 RPM motor with a 50% derated armature chopper, as discussed above, the required base drive power supply output power is approximately 40% of the ITV design. As a result of the reduced LPS input power requirement, it is possible to use the accessory battery (12V) to power the LPS. Since the accessory battery voltage variation, ±17%, is considerably less than the ±46% existing on the 108V propulsion battery, less regulation simplifies the design. An additional option (although not exercised for this study) available when the LPS is operated

from the accessory battery uses off-the-shelf modular printed circuit board mounted DC/DC converters to supply the +5V, ±15V logic power. LPS operation from the 12V battery yields reduced noise with fewer transient conditions compared to operation from the 108V battery.

Figure 3-5 illustrates the block diagram of the LPS used for costing the EDSS for the PEV.

Productization of the On-Board Charger Power Unit requires packaging and component modifications. Figure 3-6 illustrates the unit's block diagram. Its primary functions include: EMI filtering, ground fault current interrupter circuit, detection of either 15 A or 30 A power source, and safety power circuit breakers. Cost reduction of the On-Board Charger Power Unit is primarily due to quantity discount on components and automated assembly.

B. Large Scale Integration Reduces System Costs

Large Scale Integrated Circuits (LSI) as well as Medium Scale Integrated Circuits (MSI) reduce material and labor cost for the PEV EDSS. Nearly all discrete semiconductor devices have been eliminated in the control functions. Initially, in the redesigned circuit, the control functions were configured with low power MSI circuitry using a minimum number of discrete devices (resistors, transistors). VMOS devices are used with this design to interface the logic control functions with the power semiconductors, eliminating magnetic components from the ITV design. Further cost reduction is achieved by replacing multiple MSI devices for particular functions with custom LSI. In other portions of circuitry, Hybrid Integrated Circuits (HIC's) integrate several MSI circuits and discrete resistors into a single

FIGURE 3-5. EV LOGIC POWER SUPPLY BLOCK DIAGRAM

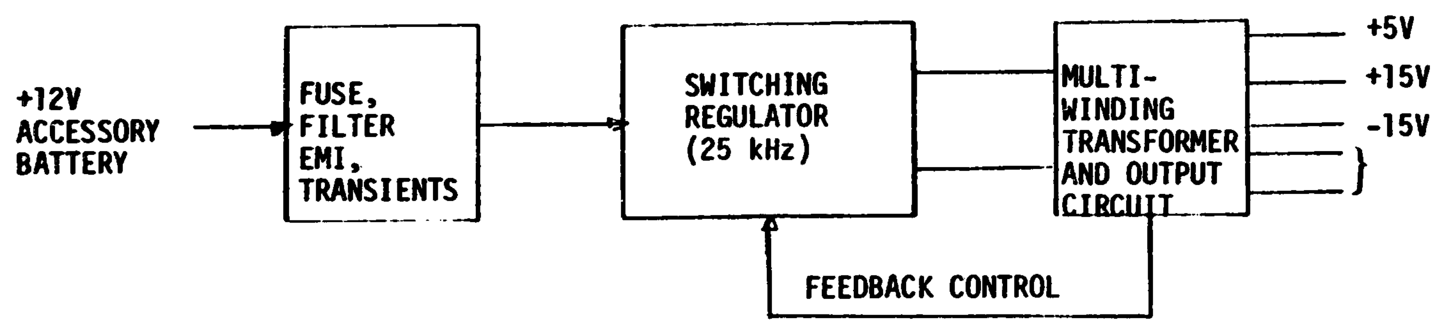
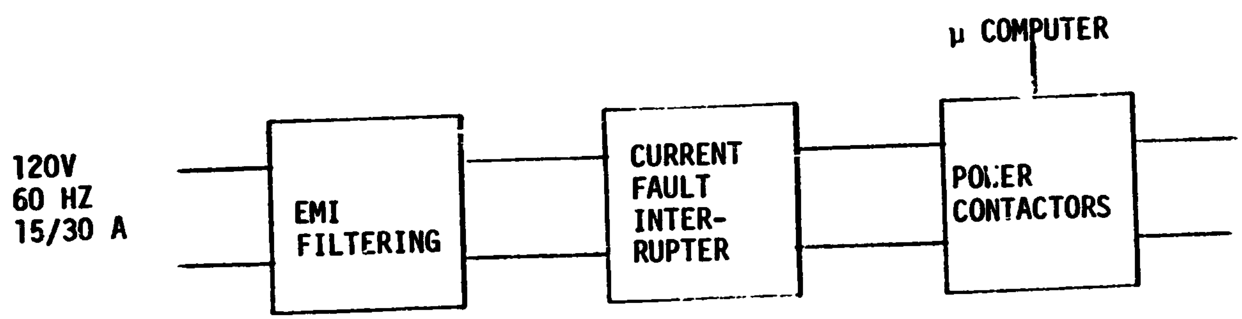


FIGURE 3-6. ON-BOARD CHARGER POWER UNIT BLOCK DIAGRAM



IC. LSI implementation reduces the number of components, which reduces both assembly and testing labor. LSI also tends to require less power, reducing the size and cost of logic power supplies.

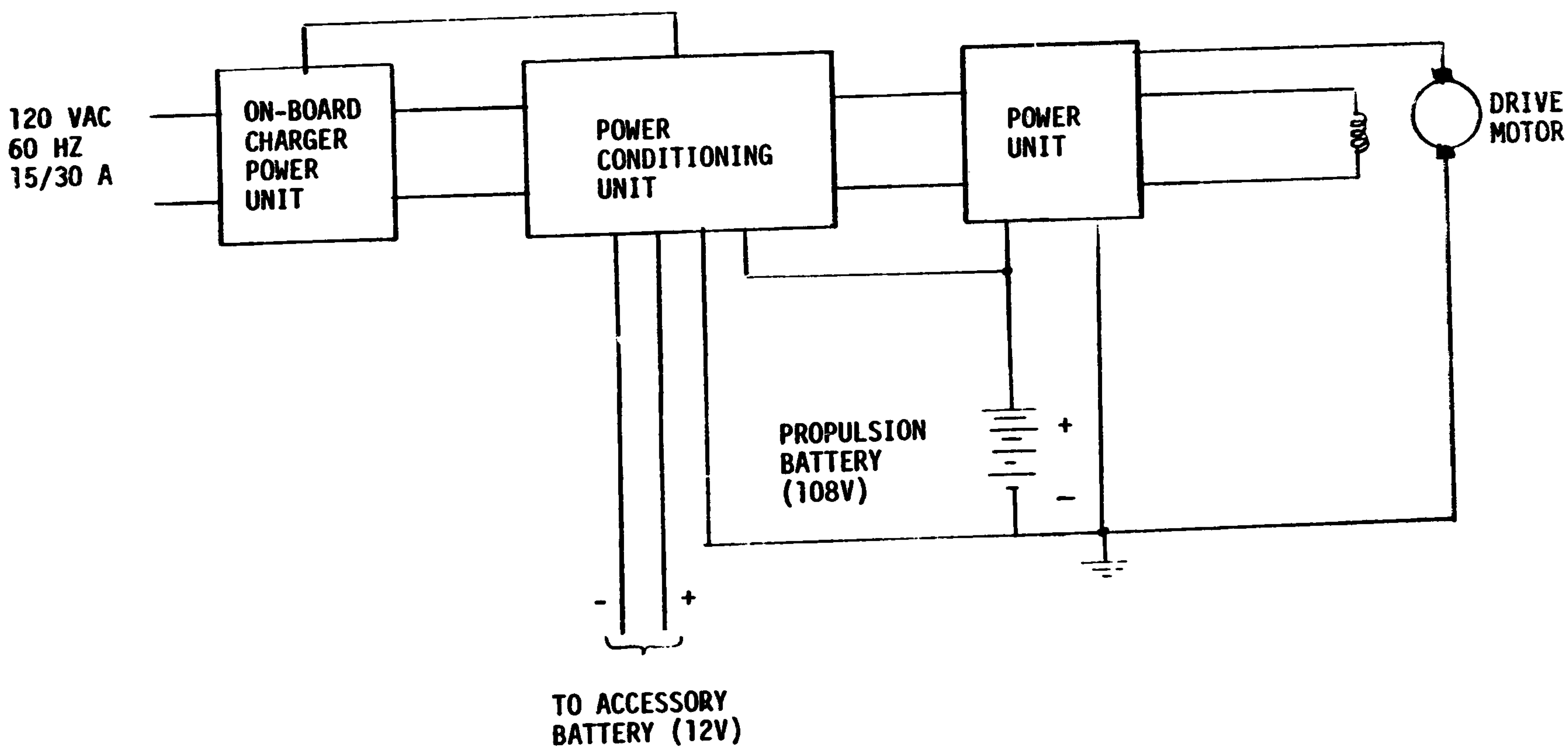
Production cost estimates for the LSI implementations were obtained from vendors and by comparison with similar LSI components used by General Electric's manufactured electronic systems. Detailed information of integrated circuit packaging and functional partitioning is presented in the following section.

C. PEV EDSS Component Packaging

Reduction of the physical size of the EDSS components in the PEV allows alternate low cost packaging concepts. Cost optimizations, presented in previous sections, suggest that PEV functional partitioning different from the ITV EDSS are utilized. This section presents these packaging concepts at the module and board level.

Production Electric Vehicle (PEV) EDSS contains three electronic modules; i.e., Power Conditioning Unit (PCU), Power Unit (PU), and the On-Board Charger Power Unit. The PCU module contains the Electric Vehicle Integrated Control function, battery charger functions, and logic power supply. The Power Unit module contains the base drive functions and power component function. Power semiconductors, for armature and field choppers, power filters, plus main and bypass contactors are included in the power component function. Figure 3-7 illustrates the interrelationship of each module in the EDSS of the PEV.

FIGURE 3-7. PRODUCTION ELECTRIC VEHICLE ELECTRIC DRIVE SUBSYSTEM



Electric Vehicle Integrated Control (EVIC) function contains the μ computer with its input/output interface circuitry plus all the armature chopper logic and field reversing logic. The complete electric vehicle integrated control function is implemented on a single board containing 13 Dual In-Line Package (DIP) IC's. Since there are no discrete devices on this board, automated manufacturing, assembly and testing is used extensively.

The second board in the PCU contains the combined battery charger (108V and 12V) and the logic power supply. Transformers are potted and mounted directly on the rear of the board with leads protruding through the Printed Circuit (PC) board to be manually soldered. All electronic components are mounted, reflow soldered and tested prior to mounting the magnetic components on the rear of the board.

Both PC boards in the PCU plug into a PC backplane containing sockets and required terminal blocks for interconnecting wiring harnesses. This modular PCU design facilitates system testing and vehicle field maintenance. PCU field trouble shooting requires replacing a particular board with a "known good" board and shipping the failed board back to the factory for rework. The PCU is housed in a low cost lightweight molded case.

Low cost power unit packaging for the PEV includes the following: adequate power semiconductor cooling capability, minimal cable resistance and inductance from batteries to power unit to drive motor, lightweight, and convenient accessibility for assembly and maintenance. A power unit package solution, incorporating the above features, integrates the PU into

the drive motor end bell. However, to minimize the effect of the power unit on the motor design and mounting, the power unit is packaged in a low cost aluminum die cast shield that is bolted to the existing end bell. Cooling is provided via natural convection using finned construction and forced convection by diverting a portion of the air from the motor blower fan through the power unit. Using a 50% derated armature chopper, resulting from a 1750/5000 RPM motor as discussed in Section 3A, the entire power unit, including the base drive PC board is mounted within the motor end shield. Power filter capacitors and power contactors with built-in shunts are also mounted within the shield. Depending on the total resistance of the battery, cable and motor, an additional bypass contactor with series power resistor may be necessary to limit the current. This mode would provide additional torque for starting from "pot holes" or on very steep grades.

The on-board charger power unit is mounted in its own housing as a safety feature to avoid injury in event of a 120 VAC grounding problem. Slight modifications in the design reduce the assembly and testing labor. Component mounting is facilitated via a molded base plate and housing.

Although the drive motor used in the PEV is heavier than in the ITV design, the estimated EDSS net weight is 25 pounds lighter than the ITV design.

B. Cost Estimating Methodology

Two cost estimation techniques were used to estimate manufacturing costs in this producibility analysis. The first technique, used for PEV EDSS major subcontractors (propulsion batteries and drive motor), obtained direct vendor quotes for 100,000 units per year. The second technique was used for the PCU, PU, and On-Board Charger Power Unit (OBCPU). This technique estimated base material cost and labor time required for each function. These estimates were multiplied by appropriate overhead factors to arrive at the manufacturing cost for each function. The acquisition (selling) price added amortization costs for plant, equipment, research and development, and profit (after taxes) to the manufacturing cost of the PCU, PU and OBCPU.

Base material costs (1st quarter 1979 dollars) of hardware required for the simplified (cost reduced) design were obtained via vendor quotes for 100,000 quantities. In cases where the vendor would not provide a quote for 100K quantities, an estimated material cost is extrapolated from vendor cost data for lower quantities. Appropriate overhead for material handling and labor costs (direct and indirect) are based on typical high quantity General Electric electronic manufacturing factors.

Required investment and development costs assumed for this producibility analysis are summarized in Table 3-1. Major manufacturing facility investments are required to efficiently produce EDSS's drive motors and electronic control systems in quantities of 100,000 per year. Automated assembly and testing is used extensively to reduce manual labor and minimize large quantity production costs. Two amortization schedules are assumed; i.e., 10 years for major plant and equipment investment, and three years for required development and component test equipment. Thus, payback

for manufacturing facility investment is added in the selling price of the first million cars, whereas payback for R&D and test equipment is added to the first 300,000 systems.

TABLE 3-1

REQUIRED INVESTMENT/DEVELOPMENT AMORTIZATION COSTS

ITEM	ASSUMED INVESTMENT ($M)	NUMBER OF YEARS AMORTIZED	ADDITIONAL COST PER VEHICLE $
Motor Manufacturing Facility	10.0	10	-- (Included in Motor Quote)
Electronic Assembly Facility	6.0	10	6.0
Custom Chip Development	.50	3	1.67
Software Development/ Modifications	.3	3	1.00
System and Component Automated Test Equipment	1.0	3	3.33
Production Prototype Development	3.0	3	10.00
TOTALS	$20.8M		$22.00/EDSS

III. CONCLUSIONS

Manufacturing and selling price estimates for a Production Electric Vehicle (PEV) Electrical Drive Subsystem, with vehicle performance equal or superior to the ITV, are presented. Cost estimate results are based on a cost reduced version of the EDSS for the ITV. Typical overhead rates for material and labor were used. Automated assembly and testing procedures are used to reduce labor costs.

Cost estimates presented, based on simplified models, are believed to be reasonably accurate. However, test data from the ITV and the development and cost optimization of a production prototype electric vehicle are required to establish an improved cost estimate of the EDSS for a PEV.

Section 4 Attachment F

REQUIRED MOTOR AND CONTROLLER DATA

FOREWORD

In order to conduct the hybrid vehicle design trade-off studies, considerable input information and data were needed. This section contains the motor and controller data which were requested.

P. O. BOX 43
SCHENECTADY, N. Y. 12301

DIAL COMM 8*235-7989

GENERAL ELECTRIC

CORPORATE RESEARCH AND DEVELOPMENT

TO: F.G. Turnbull

FROM: A.F. Burke

DATE: November 10, 1978

SUBJECT: Information/Data Required on AC Motor/Controller Drive Systems for the Hybrid Vehicle Design Trade-Off Studies

As part of the hybrid vehicle design trade-off studies, I need information/data on ac drive systems. This data will be used in both the screening and comparison of various power-train configurations and the simulation of hybrid vehicle operation over various driving cycles. Computer programs which use the requested data as inputs and for modeling of the various components currently exist and are being readied for running on the GE computer. (The programs were developed while I was at JPL.) Detailed information/data is needed for ac drive systems in the following size range:

Continuous rating: 15 - 35 KW

Peak rating (30 seconds): 30 - 70 KW

The information/data needed for the ac motor and inverter/controller are listed in detail separately for each component in Tables I and II. In short, I need information on the size and weight, torque and rpm, current and voltage, loss and efficiency, scaling, and cost characteristics of the ac components. I realize that for some of the parameters there may be a significant uncertainty*, especially in projecting the 1978 state-of-the-art to the 1981-1985 time period. It is important that those instances be noted and some measure of the uncertainty be given either as a range of values or a band of curves.

Scalability of the information/data to drive systems in the range of interest is important as it is not possible in this early stage of our work to know the exact size (KW) of the electric drive system needed in the 5-passenger hybrid vehicle we are studying. Scalability can be given in terms of

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* There are probably even different design approaches that may be taken. I leave it to you to decide when results should be given for different types of motors and/or inverter/controllers.

"specific" values of the characteristics (ex. lb/KW, in^3/KW, $/KW, etc.) and/or models (i.e. analytic expressions) for currents, voltages, losses, etc. referenced to a baseline component size.

I need this information on ac drive systems by the end of November, if possible, and by mid-December at the latest. The information can, of course, be updated and expanded over the following few months.

A.F.B.

/dll
Enc.
cc: R.H. Guess

TABLE I

INFORMATION/DATA FOR AC MOTORS FOR VEHICLE DRIVE SYSTEMS

(1) Weight vs. KW-continuous rating

(2) Volume (dimensions are preferred) vs. KW-continuous rating

(3) Over-load factor for accelerations (30 seconds)

(4) Normalized maximum torque curve [T/To vs. RPM/(RPM)]

(5) Current-voltage vs. torque and rpm using optimum control

(6) Scaling rules (sizing and losses)

(7) Voltage level trade-off considerations

(8) Loss calculation procedure or efficiency vs. torque and rpm using optimum control

(9) Efficiency for regenerative braking

(10) Estimated cost vs. KW-continuous rating

TABLE II

INFORMATION/DATA FOR AC INVERTER/CONTROLLER

(1) Weight vs. KW-peak rating

(2) Volume (dimensions are preferred) vs. KW-peak rating

(3) Loss calculation procedure or efficiency vs. current-voltage

(4) Transient current characteristics as seen by the battery for drive and braking modes

(5) Scaling rules (sizing and losses)

(6) Estimated cost vs. KW-peak rating, including listing of high cost components

(7) Motor start-up and control options